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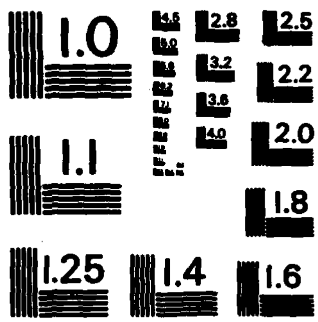

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A COMPUTER AIDED MULTI-MAN-MACHINE WORK AREA
DESIGN AND EVALUATION SYSTEM - MAWADES

By

Babur Mustafa Pulat

ONR Contract Number N00014-81-C-0320

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FINAL REPORT

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→ MAWADES

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

MAWADES (Multi-Man-Machine Work Area Design and Evaluation System) is a computerized design tool for a human factors specialist. It has been developed for designing the work-space of a crew for command, communications, and control activities at sit-stand duty.

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The first module in the MAWADES model is WOSTAS. Workstation Assessor (WOSTAS) accepts mission oriented task requirements, and ~~utilizing~~ scheduling and line balancing concepts, generates alternate scheduling schemes of tasks to workstations. Then the

WORG (Work-space Organizer) ~~follows next in~~ the model. ~~This~~ module generates ergonomically sound layouts of the workstations within the work-space. Workstations are laid out according to calculated link values between them.

which

The third module ~~in sequence~~ is WOLAG (Workstation Layout Generator) ~~(WOLAG)~~ has been designed to generate panel layouts at each workstation. Displays and controls are laid out sequentially on a panel based on system functions and operational relationships between panel components.

used

An existing model, SAINT (System Analysis of Integrated Network of Tasks), is ~~utilized~~ for dynamic evaluation of suggested alternative designs. Other evaluation criteria (static) applied through the first three modules also help in the decision making process. Originator-supplied keywords include: Computer-aided design, work-space design, and crew station design.

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INTRODUCTION

Since the early nineteen forties, a classical area of human factors research has been the design of the work-space in accordance with system functions and requirements, along with human capabilities and limitations. The major design variables that have been investigated are; the environment (lighting, temperature, noise, etc.) the man-machine compatibility including dimensional and arrangement relationships, personal factors, and work and task organization.

Most of the research done on work-space design deals with cases where the man-machine system involves only one operator. There are only a few prescriptive studies in literature which specifically address the problem of designing crew environments. Thomson (1972) lists a number of factors that should be taken into account in designing multi-man-machine work areas. These range from environmental and safety factors to human dynamics, visual and communication requirements. Thomson also proposes use of link analysis in arranging workstations, checking adequacy of visual angles and lines of sight, and planning the layout around system requirements. Some of the other studies which concentrate on general design requirements are those of Larsen (1977), Leebeek (1974) and Merkle (1973). The main theme of these research efforts is that the final design should accommodate the needed crew size, be compatible with the mission and ergonomic design requirements, and optimize group efficiency.

Application studies in crew station design stress functionality in the final man-machine system configuration. In this respect, important information needs of the designer center around statement of the mission of the crew, information and equipment needs to perform the duties, and procedures and manning necessary for operations under extraordinary conditions. Some such studies are by Murphy (1977),

Abramowski (1976), Harper (1974), Mackay (1974) and Janousek (1970).

None of the above studies approach the problem of crew station design from a systems viewpoint. This study presents a model to this end.

MAWADES Model:

MAWADES (Multi-Man-Machine Work Area Design and Evaluation System) is a computerized decision support tool developed for designing the work-space of a crew for command, communication, and control activities. It is assumed in the model that the operators perform their duties through instrument panels at sit-stand duty. Unlike conventional crew station development efforts using mockups and written guidelines, this methodology makes use of a computer throughout the design process. Thus, several alternative configurations of the system can be developed much faster and at significant cost savings. Changes, even major ones, can readily be factored into the design process and evaluated. This model may also be used in conjunction with conventional techniques for greater efficiency and flexibility.

Figure 1 gives the structure of the MAWADES model. WOSTAS (Workstation Assessor) accepts mission oriented task requirements, and generates information such as total number of workstations, task to be performed at each workstation, and other pertinent data.

WORG (Work-space Organizer) generates alternate layouts of the workstations within the work-space, based on operational relationships between the stations. WOLAG (Workstation Layout Generator) then designs the instrument panel layout at each workstation. Dynamic evaluation of alternate designs is carried out through the SAINT (System Analysis of Integrated Network of Tasks) model, which was originally developed in early seventies as a general purpose man-machine system simulation model (Pritsker et al., 1974).

MULTI - MAN - MACHINE WORK AREA DESIGN
AND EVALUATION SYSTEM - MAWADES

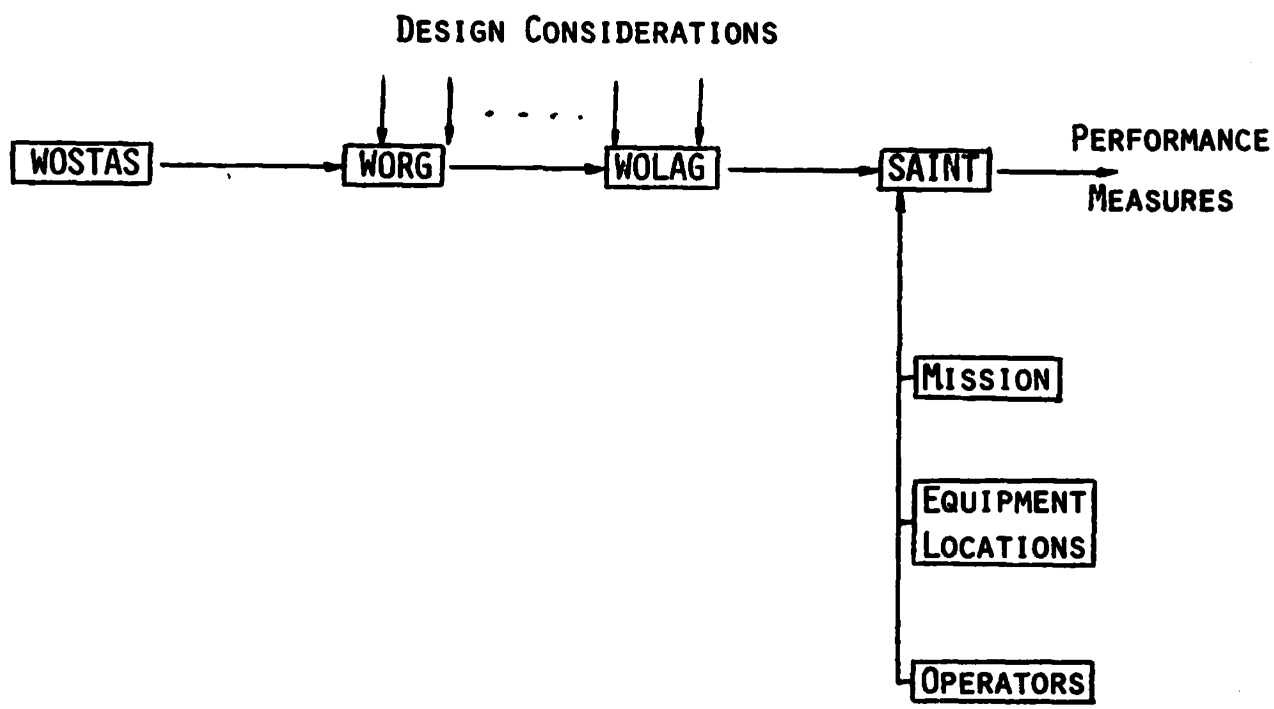


Figure 1. Model Structure

WORKSTATION ASSESSOR - WOSTAS

WOSTAS accepts mission oriented task requirements and utilizing scheduling and line balancing concepts, generates alternate scheduling schemes of tasks to workstations. WOSTAS also collects evaluative measures on each scheduling scheme which may be analyzed by a decision maker to find the best one. This may involve weighted and/or unweighted combinatorial analysis of all evaluative measures under other constraints, such as available manpower, cost, available space etc.

WOSTAS bears resemblence to the classical Assembly Line Balancing problem in that, it too involves grouping of tasks adhering to the precedence relationships between tasks, and balancing work loads at different workstations. Assembly Line Balancing has been the subject of considerable research in the past few decades. It involves the movement of a manufacturing unit from one worker to the next. The manufacturing process consists of a set of tasks, performed in a given sequence, to complete the product. These tasks are divided among the available workers such that a worker performs the same operations on every unit. The time spent by every unit at a given workstation is known as the cycle time. The division of tasks is subject to several constraints e.g. precedence relationship, and zoning constraints dictated by the nature of the product. Several representative ALB models are by Salveson (1965), Adam and Elbert (1978) and Schonberger (1981).

The classical ALB models assume that every task requires the same types and levels of abilities on the part of the operator. In WOSTAS, this assumption has been relaxed. Hence, tasks are grouped such that the ability levels (intelligence, perceptual, psychomotor, language) needed are compatible, and all tasks at a given workstation can therefore be performed by the same worker(s). Assuming that a

sound employee selection program has been exercised, this may help minimize training time.

Another factor which most techniques ignore is the tiring constraint i.e., the amount of physical effort which goes into completion of actions. A better solution to the problem would balance the demand for physical effort at each station.

Further, ALB techniques are developed on the assumption that the sequence of tasks to be performed is deterministic. It is possible that any piece of information presented through the displays on the instrument panels, or generated as a result of an activity may require different actions depending on the type of information presented. Thus, in our case, the mechanics of the classical ALB were adjusted to allow for probabilistic branching. Operators are now allowed to go with alternate tasks or set of tasks to prevent bottlenecks or compensate for unusual situations. The probability of the choice of alternate task routes may be determined on the basis of historical data on existing systems. For new systems, this data should be derived from the experience with similar systems.

Inputs:

The data needed for the module are as follows:

a) A representative mission of the crew in network form with activities (tasks) and their durations. For tasks which are expected to show fairly large variations in performance times, mean durations are input.

b) Minimum and maximum allowable cycle times (the time during which each workstation is expected to complete the required duties), along with a step size. The step size is a time increment which is added to the previous cycle time value to obtain a new cycle time and perform another iteration (scheduling of tasks to workstations). The program terminates when the final iteration (corresponding to the maximum cycle time) is completed.

c) For each task in the network representing the mission, codes indicating the extent of requirement (low (1), medium (2), high (3)) for language, intellectual, perceptual, phychomotor abilities. Tiring (physical effort demand) characteristic of each task is also input through the same coding system. A separate rating for the extent of observing these restrictions during assigning tasks to workstations is also required. Assuming a ratio scale between 1 (low) and 10 (high), these codes allow for weighted analysis of ability restrictions in the model.

d) Other user requirements such as probabilities of taking alternate paths of action at tasks which require probabilistic branching, and priority constraints. The priority constraints take the form of user enforced grouping and/or separation of tasks at or from any workstation. These are overriding constraints which allow the user to make apriori decisions at some workstations as to grouping certain tasks due to, for instance, the use of a special device. The tasks in the user enforced separation file are allocated to different workstations.

Description of the ability requirements for each task in the mission is justified here. Four are identified in (c); intellectual, perceptual, psychomotor, and language. Intellectual ability is characterized by one's capacity to deal efficiently with tasks characterized by difficulty, complexity and abstractness. It is also the capacity of an individual to absorb and perform new and varied activities. In an information processing system such as the one indicated in this study, several specific origins for demand for intellectual abilities are:

a) Capacity to effectively evaluate information input to machines

b) Capacity to follow both general and specific instructions

c) Capacity to develop procedures for solving problems during the mission

d) Capacity to improve operating procedures.

Perceptual abilities in terms of capacity to detect fine color, size, shape, distance, and sound differences are important if one is to perform an information processing task well. Such capacity is also emphasized when vigilance decreaments are expected, and when reaction time to signals is of critical importance.

The term psychomotor refers to observable voluntary human motion. In the context of this system, high psychomotor ability demands acquired proficiency in performing complex tasks with skillful movements.

Language in any form is a tool of communication. Because in any voice communication task two parties are involved, both should be in agreement as to the meaning of different words involved. Many cases require persons conversant in the technical jargon prevailing in the area. More information can be obtained in the abilities discussed above from Coleman (1969), Combs et al. (1976), and Fleishman (1967, 1972, 1975, 1979).

Module Structure:

Figure 2 gives the flowchart of WOSTAS. The following define the important parameters of the model:

CT: Cycle Time

SS: Step Size

WS: Workstation

RCT: Remaining Cycle Time at any workstation

List A: Contains all tasks not already assigned to any workstation

List B: Contains all tasks with no predecessors or all predecessors already assigned

List C: Contains all tasks whose expected durations are $\leq$ RCT.

After all the data have been read in, the first major step is the calculation of expected task durations. Although each task has a distinct duration input by the user, some of the tasks may be on probabilistic branches, and thus, not realized everytime the mission is undertaken. Furthermore, since the work-space needs to be structured around the performance of the system in the long run, expected duration of the tasks need to be calculated and work-load balancing decisions be made on these durations. This approach may occasionally result in more than and less than adequate working requirements at several workstations (which will balance out in the long run), but will certainly eliminate scheduling decisions depending on the paths followed in the mission. Naturally, tasks which lie on non-probabilistic branches assume user input durations as expected durations.

The expected duration of task i is calculated as follows:

$$ED_i = PR_i * DD_i$$

where:

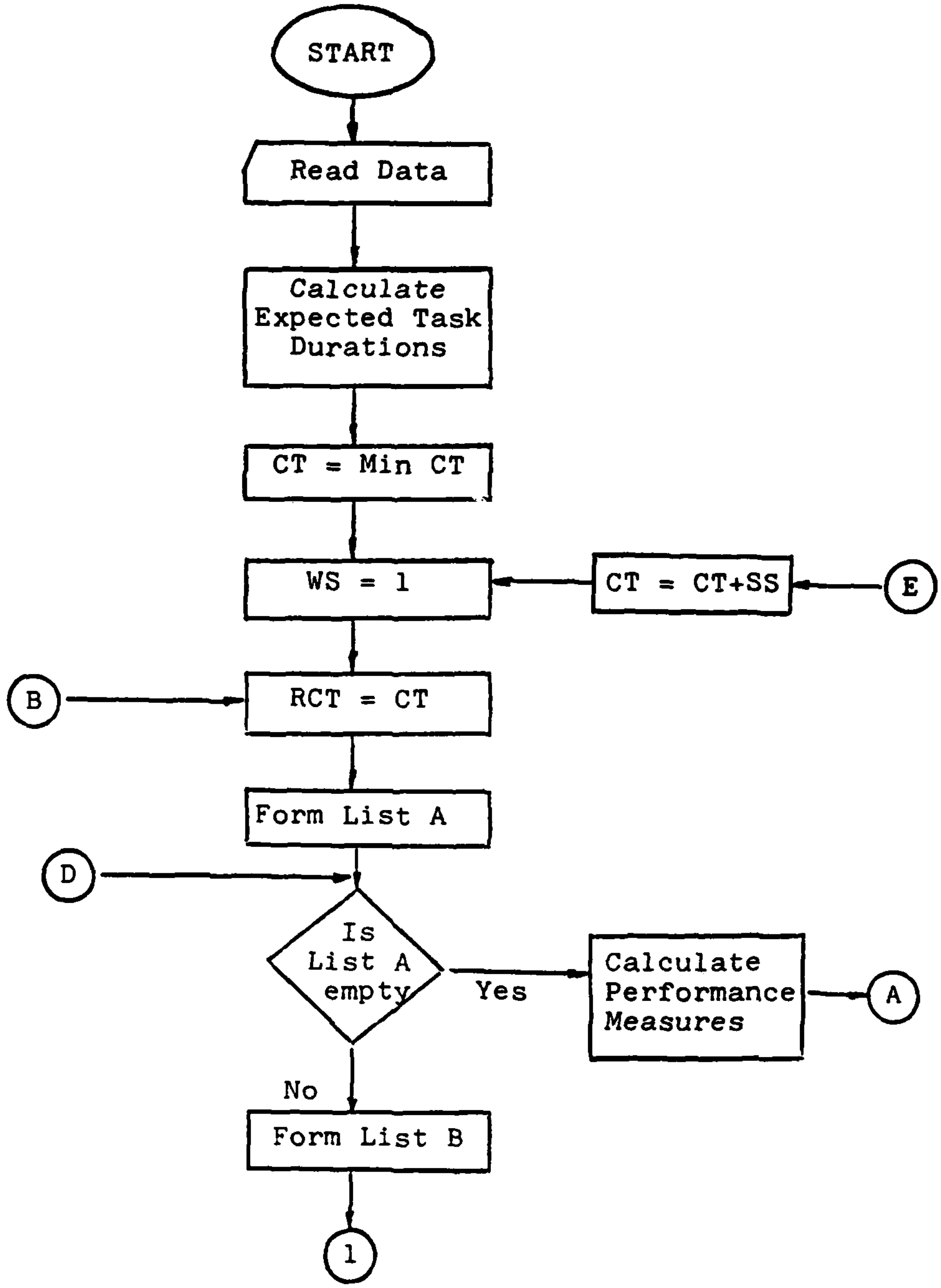
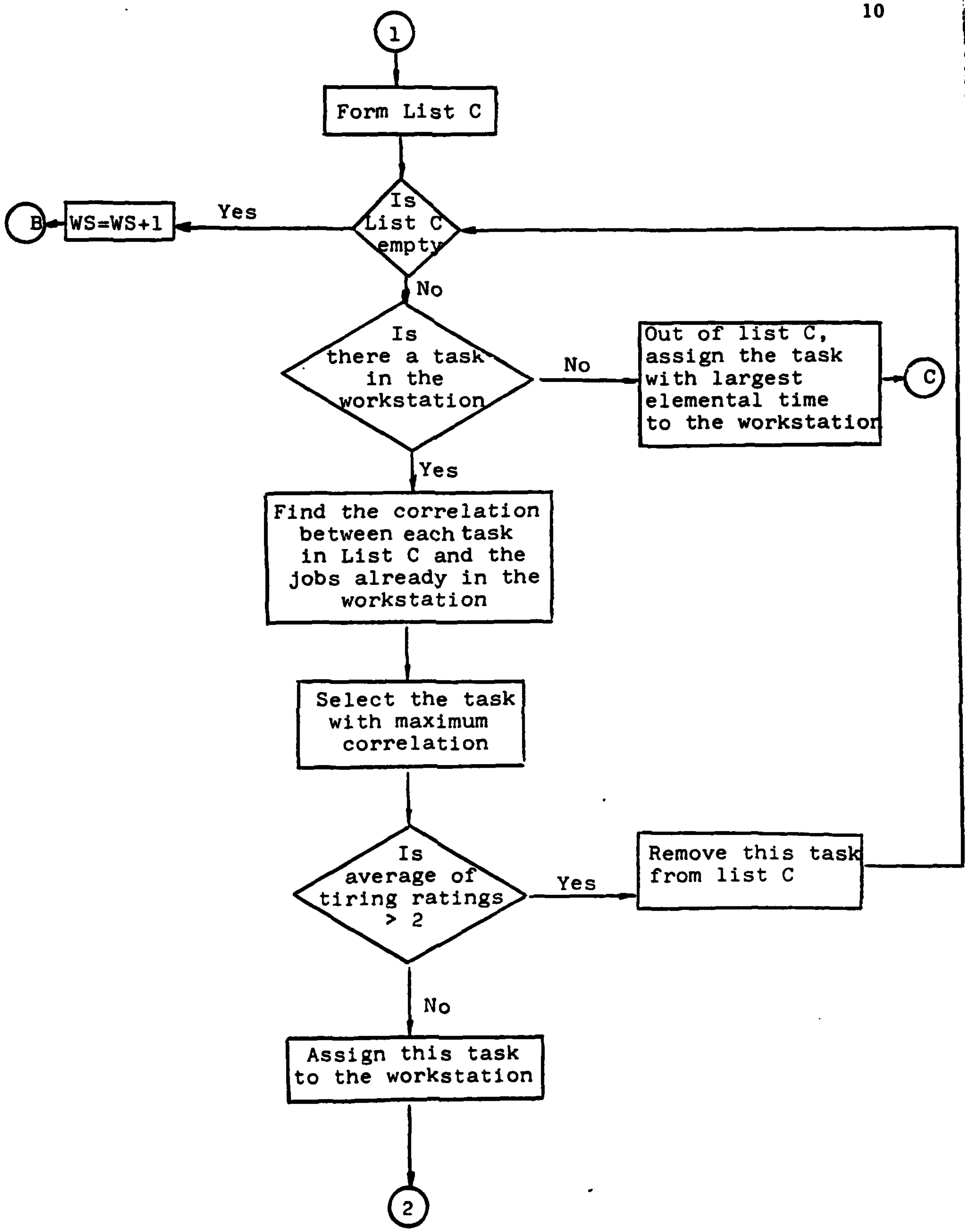


Figure 2 WOSTAS Flowchart



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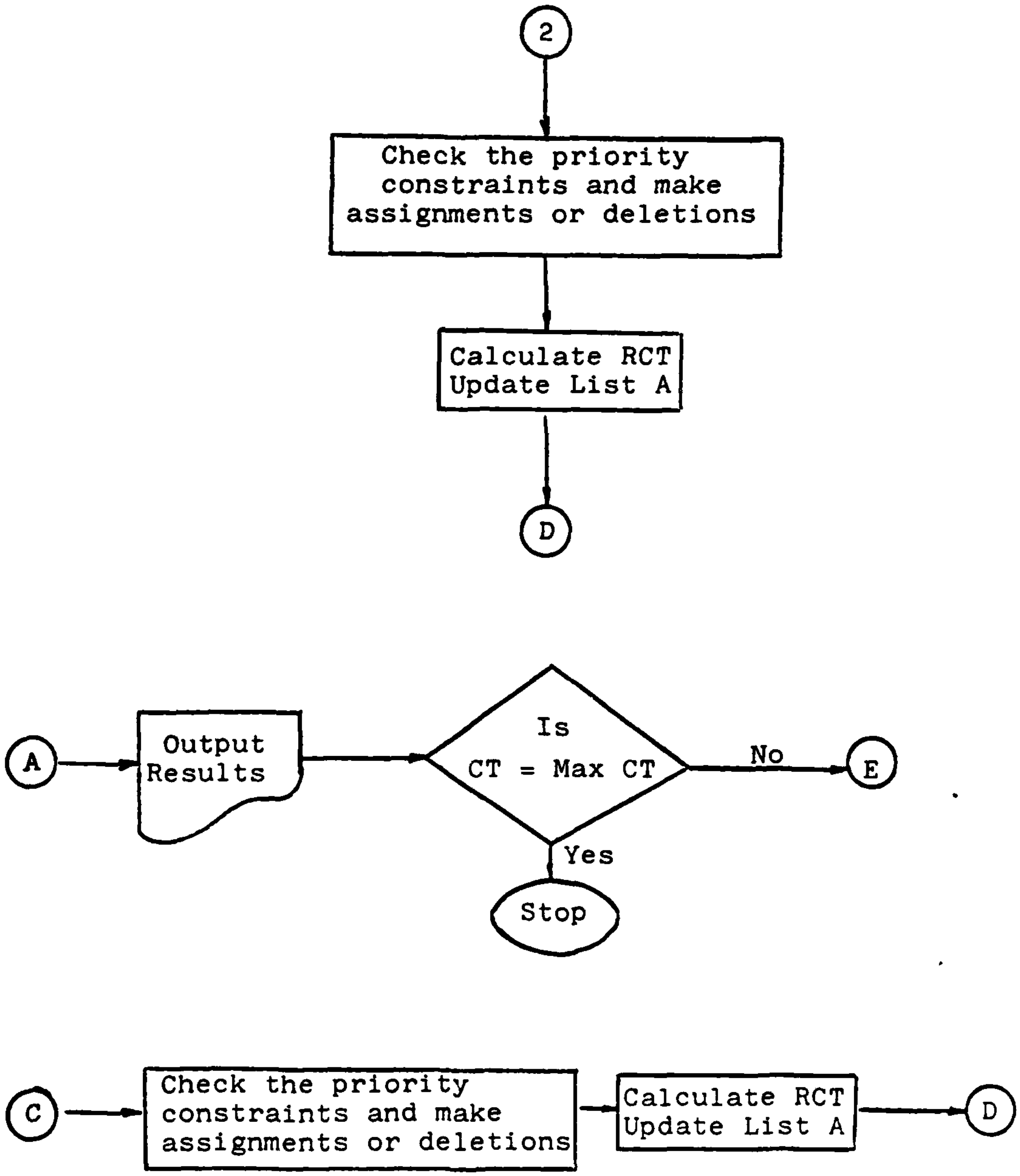


Figure 2 (continued)

ED_i: Expected duration of task i

PR_i: Probability of realizing task i

DD_i: Deterministic duration of task i (user input)

The probability of realizing task i depends on the probabilities of branches entering the node representing the task, and the total number of such branches (arrows). Finding analytic means of calculating task realization probabilities is difficult on a network involving hundreds of tasks. In WOSTAS, these probabilities are calculated through simulating the mission using the MONTE CARLO approach (Render and Stair, Jr., 1982) and obtaining information on each task's total number of realizations. This number, divided by the total number of simulation runs gives the realization probability for each task.

Tasks are assigned to the workstations starting at Station 1, continuing towards Station i. While making assignment decisions at any station, the candidate task list is composed of:

A. The Tasks whose predecessors have already been assigned and whose expected durations are less than or equal to the remaining cycle time (RCT) at the station.

B. Tasks which appear in the user enforced grouping file.

Depending on the case involved, a task from either file A or file B is assigned to the station. If a task from file A is selected, it is the one that correlates best with respect to ability indices with the tasks already assigned, with no more than medium (2) overall average tiring rating at the station.

For any task j, the ability indices are calculated as follows:

$$W_{ij} = \frac{OC_{ij}}{\sum_{i=1}^{4} OC_{ij}} \qquad i = 1,..,4$$

where

W_{ij} is the weight of ability i on task j.

OC_{ij} is the observance code for the ability on task j (see input data category C).

Then:

$$AI_{ij} = AC_{ij} * W_{ij} \qquad i = 1,..,4$$

where

AI_{ij} is the ability index for ability i on task j.

AC_{ij} is the ability requirement code for ability i on task j (see input data category C).

W_{ij} is the weight of ability i on task j.

Suppose that for task 3, the user has input the following data:

	Ability Categories			
	Intellectual i = 1	Perceptual i = 2	Psychomotor i = 3	Language i = 4
Observance Code	7	5	5	8
Ability Requirement Code	2	2	3	3

Then;

$$W_{13} = \frac{7}{7+5+5+8} = \frac{7}{25} = 0.28$$

$AI_{13} = 2 * 0.28 = 0.56$ (Intellectual Ability Index).

Similarily;

$$W_{23} = \frac{5}{7+5+5+8} = \frac{5}{25} = 0.2$$

$AI_{23} = 2 * 0.2 = 0.4$ (Perceptual Ability Index).

W_{33}, AI_{33}, W_{43}, and AI_{43} can be obtained similarly. The above procedure has been developed using the weighting concepts developed by Arcus (1966).

Once the candidate task list is empty for a workstation, next station is scheduled with tasks on a new candidate list. One iteration is completed when all tasks have been scheduled to workstations. Depending on the current cycle time, this may result in j number of workstations, each to be manned by one operator, thus, requiring j number of operators in total for the mission. After every iteration, performance measures are collected on the scheduling scheme for the iteration.

A total of (max CT - min CT)/SS number of iterations are performed at each run of the model. This allows for sensitivity analysis of the performance measures to the cycle time. It also allows the user to be more flexible on the requirements of the cycle time specification. In fact, the user may take the reverse approach and analyzing the performance for all the iterations, may make intelligent decisions on the "best" cycle time.

Outputs:

At each iteration, WOSTAS outputs the following information:

1. The complete scheduling of tasks to workstations, and the corresponding cycle time.

2. Performance measures collected on the current scheduling scheme. These performance measures are:

   a) Balance delay at each workstation. This is a measure of the time expected to be free at each workstation, and is calculated as follows.

$$BD_j = CT - \sum_i ED_{ij}$$

where

BDj: Balance delay at workstation j

CT: Cycle Time

ED_{ij}: Expected duration of task i scheduled to workstation j.

In scheduling tasks to workstations, WOSTAS aims at minimizing the free time at each workstation. Since CT is constant across the workstation, at each iteration, this process helps balance the workload (timewise) across the stations.

b) Total Balance delay. This is a measure of total amount of free time across the workstations, and is calculated as follows:

$$TBD = \sum_j BD_j$$

where:

TBD: Total Balance Delay

BD_j: Balance Delay at workstation j.

It is desirable to have this value as small as possible. Comparing TBD with CT at any iteration, one may also get an idea as to how many WS equivalent free time is existing for any scheduling scheme.

c) Ability and tiring characteristics of the tasks at each workstation. The statistics collected are: Mean tiring rating of the tasks scheduled, and mean and standard deviation of the weighted ratings for ability constraints. Mean values indicate the extent of requirement for language, intellectual, perceptual, and psychomotor abilities at each workstation. Standard deviation data is a variability measure for ability requirements. Small standard deviation values indicate more homogeneous ability requirements at any workstation.

The performance (evaluative) measures are collected on each scheduling scheme to aid the decision maker find the better one. There may be other evaluative criteria for which the data may be derived from the current measures. One may be the cost. Even though a scheduling pattern which results in six workstations may be superior with respect to the current measures collected through WOSTAS, another arrangement requiring five workstations may prove to be more desirable when cost is included in the overall evaluation procedure. Furthermore, five

stations may take less space than six stations. Available manpower may be another input to the evaluation process. All of these and other measures may be subjected to combinatorial analysis to make a more intelligent decision as to how many workstations one should have within the work-space, and which tasks are to be carried out at each workstation.

Illustration:

This section gives a hypothetical example problem which is solved through WOSTAS. Inputs and outputs for the problem are explained in detail.

The mission consists of 39 tasks, and the precedence (sequence) relationships between these tasks are given by Figure 3. Here, precedence relationships are shown with arrows, and tasks are denoted by circles with tasks numbers inscribed. Numbers above the circles are the task durations. Certain arrows have numerals beside them indicating the probabilities of choosing those branches. If an arrow has no probability indicated for it, a probability value of 1.0 is assumed (i.e. deterministic branch).

Mission starts with task 1 (source task), and ends with the realization of task 39 (sink task). Three major functions of this system are implied by the mission. The first two functions are either-or types, starting with probabilistic branching at task 3. The first function, represented by tasks 5,6,7,......,30,31, 36, is expected to be performed 80% of the time. The second function, represented by tasks 8,12,13,17,18,25, and 32, is expected to be performed 20% of the time, whenever function 1 is not performed. Therefore, function 2 is a contingency function to 1. The third function of the mission is represented by tasks 4,9,10, ...,33,34,35,37 and except for a few tasks on it, is a deterministic function. Once two functions are completed, the mission ends. The probabilistic branching tasks on the mission are 3,8,16 and 14.

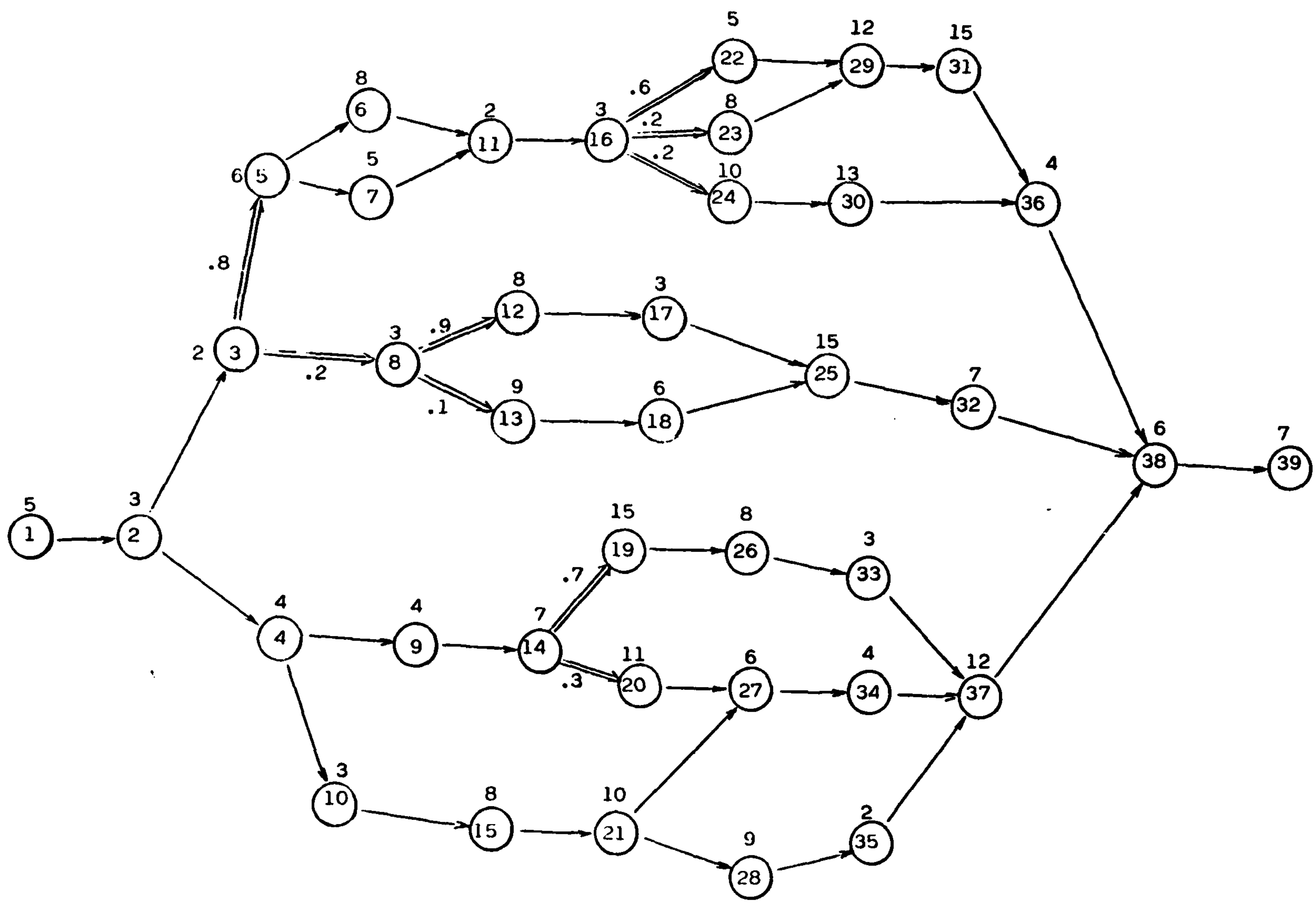


Figure 3. A representative mission for the example problem.

The user wishes to group tasks 5,12,13; 10,15,21; and 30,25; that is, the user wants tasks 5,12, and 13 to be performed at the same workstation, 10,15, and 21 at the same workstation, etc. If the cycle time allows, all of these tasks can be scheduled to the same workstation unless the user specifies at least two (one from each group) to be performed at separate workstations.

The user will have to input all this information along with task characteristics with respect to ability requirements. Minimum and maximum cycle times need to be specified also. Let us assume that min CT = 16, max CT = 35, SS = 3.

Appendix 1 gives the computer output for CT = 22,...,35. For each cycle time, several categories of information can be observed on this printout as summarized below:

a) Total number of wokstations specified

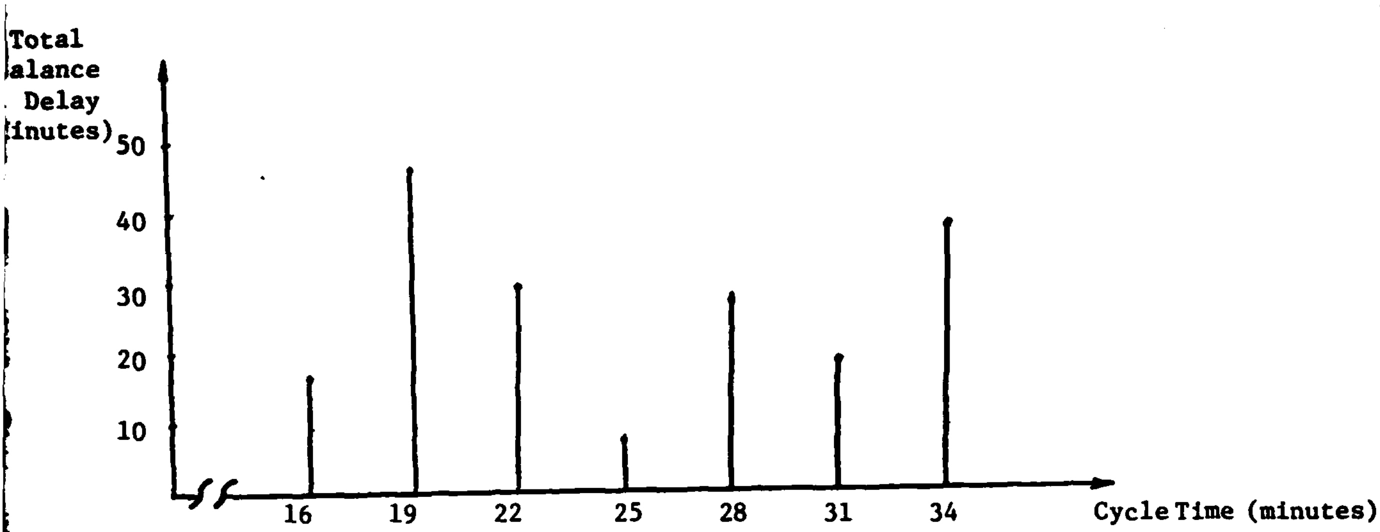
b) Tasks allocated to each workstation

c) Evaluative measures

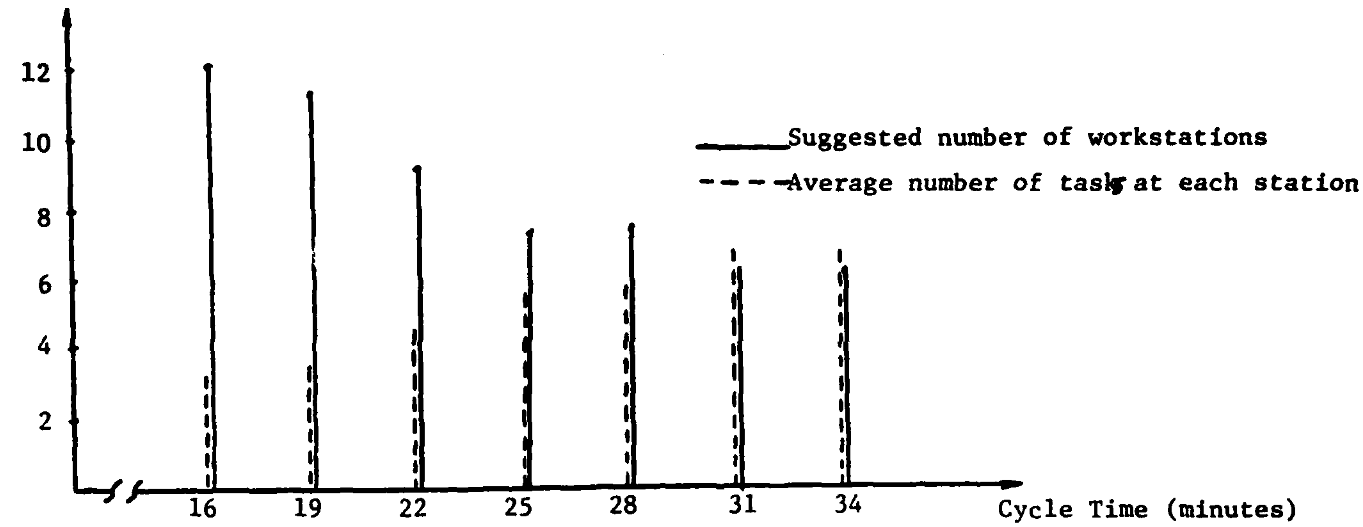
- Total balance delay
- Balance delay at each workstation
- Ability and tiring characteristics at each workstation

The plots on the next page give the sensitivity of total balance delay and balance delay at Stations 1 and 5 to cycle time. Also plotted are suggested number of workstations and mean number of tasks at each workstation with respect to changes in cycle time.

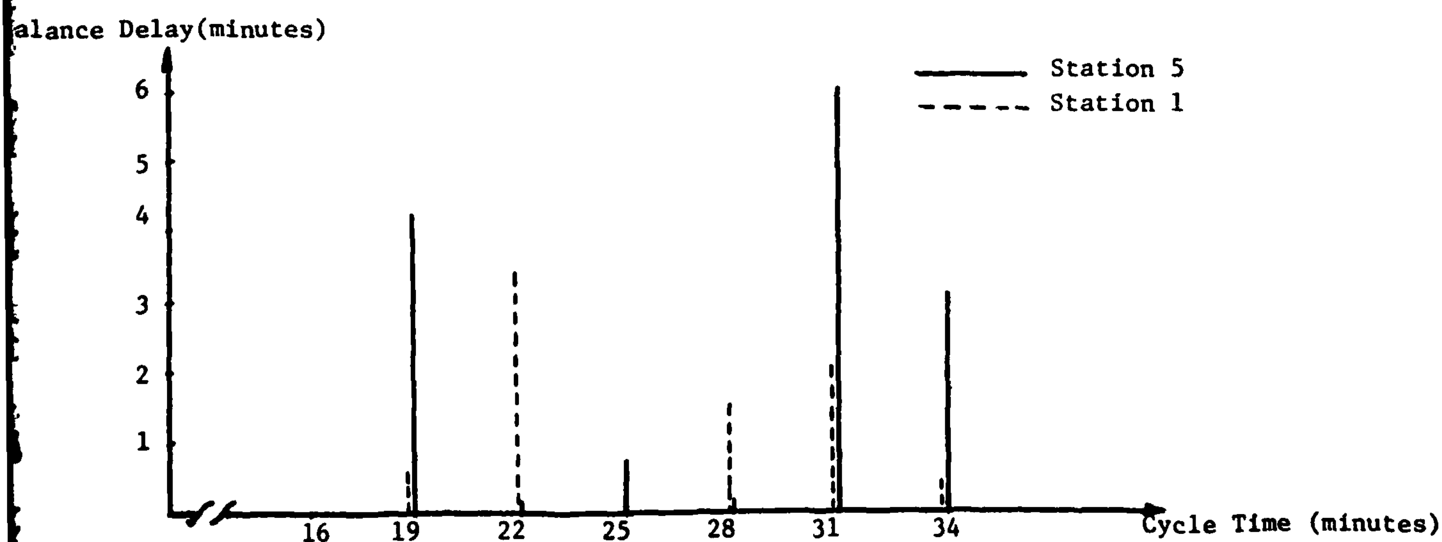
Data generated by WOSTAS may be used by a decision maker, adding more evaluative criteria such as available manpower, space and cost, to select the scheduling scheme which maximizes system effectiveness.



Total
alance
Delay
inutes)
50
40
30
20
10
16
19
22
25
28
31
34
Cycle Time (minutes)



12
10
8
6
4
2
Suggested number of workstations
Average number of task at each station
16
19
22
25
28
31
34
Cycle Time (minutes)



alance Delay(minutes)
6
5
4
3
2
1
Station 5
Station 1
16
19
22
25
28
31
34
Cycle Time (minutes)

WORK-SPACE ORGANIZER - WORG

The last decade has witnessed the development of a number of computer aided workplace design and evaluation algorithms. CAPE (Bittner, 1975), SAMMIE/AUTOMAT (Bonney and Schofield, 1973), CAPABLE (Bonney and Williams, 1977), WOLAP (Rabideau and Luk, 1975), CAPADES (Pulat, 1980) are to name a few. However, none of these models specifically address the problem of designing the workspace of a crew. WORG has been developed for the purpose of arranging workstations within a work-space. The arrangement scheme follows link values computed for between stations. These will be referred to in more detail later.

WORG is an interactive module written in FORTRAN IV programming language. It consists of a main program and four subprograms. Since the program has been structured around an interactive philosophy, the effects of input changes on the layout generated can be observed in minimal time.

Inputs:

The input data for the module are as follows:

1) General: This item includes the total number of workstations and and the total number of tasks to be carried out across the stations.

2) Workstation Information: Included here are station numbers and the operator count at each station.

3) Task Information: For each task, the following items need to be specified:

   a) Task number
   b) Area requirement of associated display or control, if any
   c) Criticality rating
   d) Predecessor count, and task numbers of preceeding tasks
   e) Successor count, and task numbers of successors
   f) Workstation assignment
   g) Sequential link (frequency-of-use per unit time) between this task and each successor
   h) Task type

Tables 1 and 2 give the codes for criticality ratings and task types respectively.

Table 1. Criticality Ratings

Task Requirements	Criticality Codes
Primary or Warning Displays	7
Primary or Emergency Controls	6
Voice Communications	5
Secondary Displays	4
Secondary Controls	3
Auxiliary Displays	2
Foot Controls and others	1

Table 2. Task Types

Task Type	Type Code
Panel - Operator	1
Panel - Panel	2
Common Panel - Operator	3
Operator - Panel	4
Operator - Operator	5

As implied in the Task Information category of the input data, the mission of the crew is represented as a network of tasks. On this network, the successors of any task are the ones which follow in the logical sequence of accomplishment. Only after completing the predecessors, succeeding tasks may be attempted.

WORG assumes that the workstation assignment of the tasks in the mission has already been done, and the operator count at each station has been determined. In the MAWADES model, WOSTAS performs these operations.

Module Structure:

Figure 4 gives the flowchart of WORG. The module has been structured such that the user does not have to input data each time WORG needs to be run. Naturally,

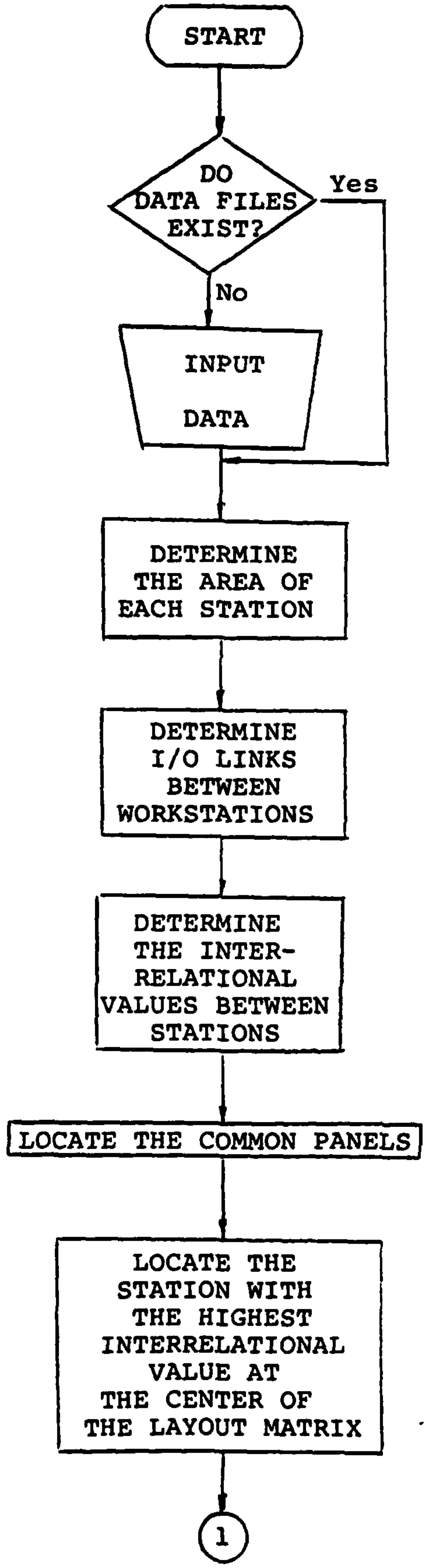
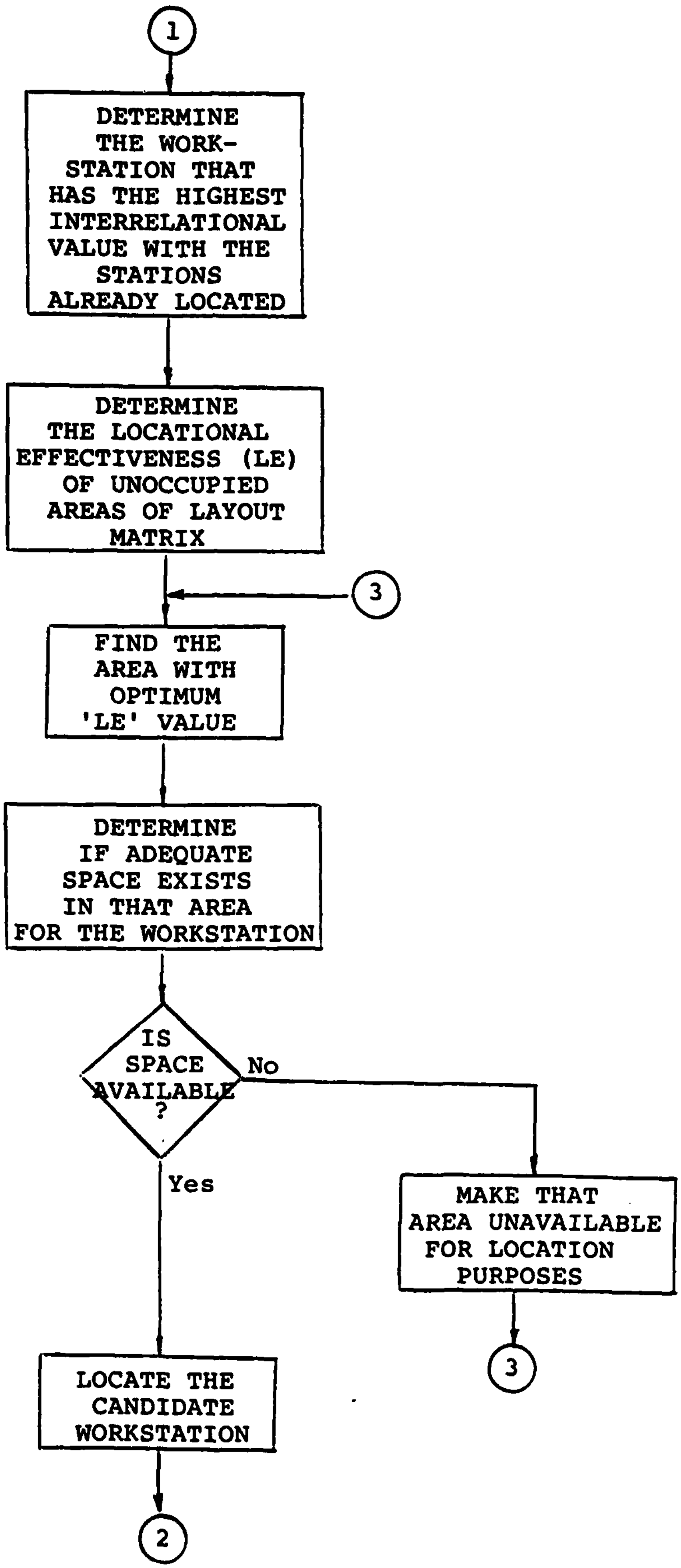


FIGURE 4 Flowchart of WORG



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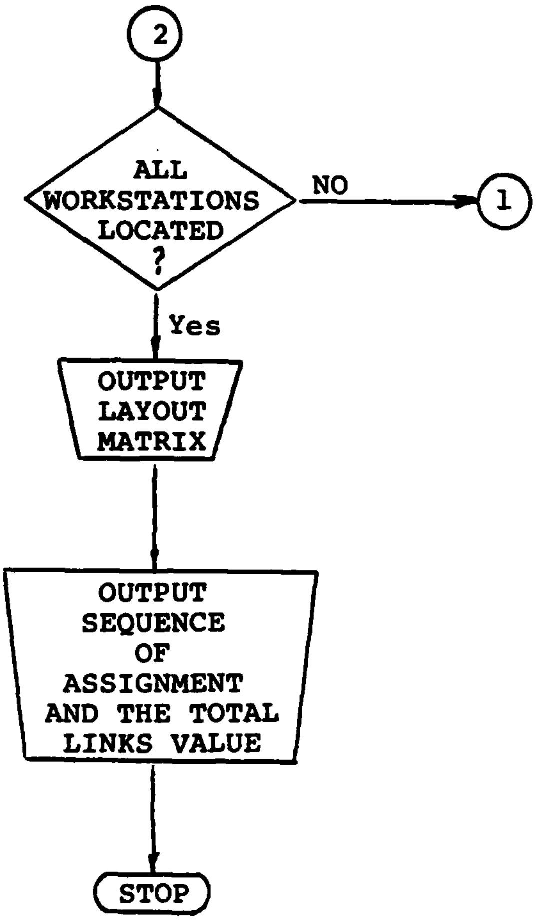


FIGURE 4 (continued)

for a new case study, data files need to be restructured. Whichever the case is, after the data have been accessed, WORG calculates the area requirement of each workstation. This includes the panel space (displays, controls, clearances, and additional space for future use), operator area(s), access and egress space, and aisle space around all four sides of the workstation (Van Cott and Kinkade, 1972; Woodson, 1981, and Diffrient et al. 1983).

Link values are then computed between stations. This is a two stage process. In the first stage, link task set is identified. The following criteria are used to detect the task couples that belong to this set:

a) The tasks must have been assigned to separate stations.
b) Both tasks should have type codes of 2, 3, or 5 only.
c) One task should either be the predecessor or the successor of the other.

At the second stage, link values (interrelational values) are computed between stations according to the following formula:

$$LV_{ij} = \sum_{\ell,m \in A} (CR_\ell + CR_m) * FR_{\ell,m} \qquad i,j = 1,\ldots,M \quad j > i$$

where

LV_{ij}: Link Value between stations i and j.

CR_ℓ : Criticality Code of task ℓ

CR_m : Criticality Code of task m.

$FR_{\ell,m}$: Sequential link between tasks ℓ and m.

ℓ,m: Tasks indentified as belonging to the link task set (A).

M: Number of workstations

Link analysis is often recommended for locating or arranging the components of a system within a given environment (McCormick and Sanders, 1982; Woodson, 1981; Huchingson, 1981). Although the recommendations as to the computation of the link values center around the importance and frequency of interrelationships between the components, there is no agreed upon format of the computation. The FR and CR values in the above equation represent the frequency and the importance of the links respectively. The additive and the multiplicative relationships place more emphasis on links that occur between critical components and less on those that occur between non-critical ones.

As the first step of the workstation arrangement process, common panels (maps, etc) are located around the perimeter of a layout grid composed of half meter squares for each grid element. Then, the workstation possessing the highest link value is located at the center of the grid. The area requirement of each station, as determined earlier, is strictly followed during the location process.

The link values file is searched to find the station which has the highest link with the one already located. Once the candidate station is obtained, for each empty grid element, a locational effectiveness value is calculated according to the following formula:

$$LE_j = \sum_i ED_{ij} * LV_{ic}$$

where

LE_j : Locational effectiveness of jth empty grid element.

ED_{ij}: Euclidean distance between the centroid of the ith already located station and the jth grid element.

LV_{ic}: Link Value between the ith located station and the candidate (c) station.

A search is performed around the element possessing minimum LE value. The candidate station is located in the area if sufficient space exists. If not, search process continues around the element in the LE rank until the station is successfully located.

The search → select → locate process continues until all stations have been located on the layout matrix.

<u>Outputs:</u>

The report files of WORG are as follows:

(a) The layout grid showing the exact locations of the workstations. The relative locations of the stations are given by the relative arrangement of the station numbers on the final layout.

(b) Placement sequence of the workstations on the layout matrix.

(c) Total Links Value - This is an evaluative measure for the layout obtained. If several alternative layouts are acceptable the one which has minimum total links value will be more desirable. The measure is calculated through the following relationship:

$$TLV = \sum_{i} \sum_{j>i} ED_{ij} * LV_{ij}$$

where

TLV : Total Links Value for the layout

ED_{ij} : Euclidean distance between the centroids of the ith and jth stations.

LV_{ij} : Link value between stations i and j.

Appendix II gives the above report files for a hypothetical problem. Station 18 denotes a common panel. Each entry on the layout represents an area of half-meter square ($\frac{1}{2}$ mt x $\frac{1}{2}$ mt). Zero entries correspong to unused areas of the layout grid. The distance between the common panel

and other stations came about due to the fact that the problem did not involve many stations. In such a case, preserving the relative locations, other stations may be moved towards the common panel (which is around the perimeter) for compactness.

Station six possesses the maximum links to all others. Thus, other stations have been located around station six, which is the first station located (after the common panel) according to the "Sequence of Assignments" file.

The "Total Links" value for one layout does not have much significance. It is for evaluative purposes when several alternative designs are being considered. Minimum links value suggests desirability of the layout since one would like to have the stations with high operational relationships located closer (minimum distances indicated) together.

WORKSTATION LAYOUT GENERATOR - WOLAG

In the MAWADES model, WOLAG's function is to prepare the layout of the instrument panel at each workstation. The panel's physical features (including the height, length, and partitions) are embedded into the module. The units (displays and controls) are located sequentially on the panel, which is initially blank.

WOLAG is an interactive module written in FORTRAN IV programming language. The results of any design study will immediately be available for user interaction for sensitivity or trade-off analysis.

Inputs

As input, the following information is required:

1. General Data: Total number of workstations (panels, and the width of each panel).

2. Workstation Inputs:

   -Functional groups of units
   a) Number of such groups at each panel
   b) Group composition (member units)
   c) Group type (simo use, sequential use, or free units group).

   -Sequence-of-use between functional groups, if any.

   -For each display or control
   a) Area requirement (cm^2)
   b) Criticality code
   c) Operational relationship with other units
   d) Clearance code.

The criticality codes are similar to the ones used in WORG. However, units used for voice communications are assumed not to be a part of the panel. Thus, the codes for WOLAG range from 1 (foot controls and others) to 6 (primary or warning displays).

Operational relationships between units are entered in letter codes as follows: A: High relationship, B: Medium, C: Low relationship. These ratings denote sequential use links between pairs of displays and/or controls.

Clearance code refers to minimum recommended separation between pairs of like units. The relevant recommendations of Chapanis and Kinkade (1972) have been adopted for use in WOLAG.

The user is asked to form functional groups of units from those:

a) Which require simultaneous use of various units (simo use group).

b) Which have sequence-of-use relationship between the members (sequential use group).

c) Which do not possess any of the above two characteristics (free units group). This group may further be partitioned into sub-groups for any other reason.

It is possible to form larger functional groups of displays and controls by specifying the sequence-of-use between the subgroups.

Module Structure

Figure 5 gives the flowchart of WOLAG. As is the case in WORG, new data files may be input for a new study, or existing files may be modified and re-used for sensitivity analysis on a previously completed design study. The panel layouts are prepared in a sequential manner moving from station 1 to the last station. The basic layout process is the same across the workstations. However, due to different unit requirements and/or functional group compositions and sequence-of-use data between the functional groups, each station may obtain a different layout of the panel. The discussion that follows gives the basic steps of thé layout procedure at any workstation.

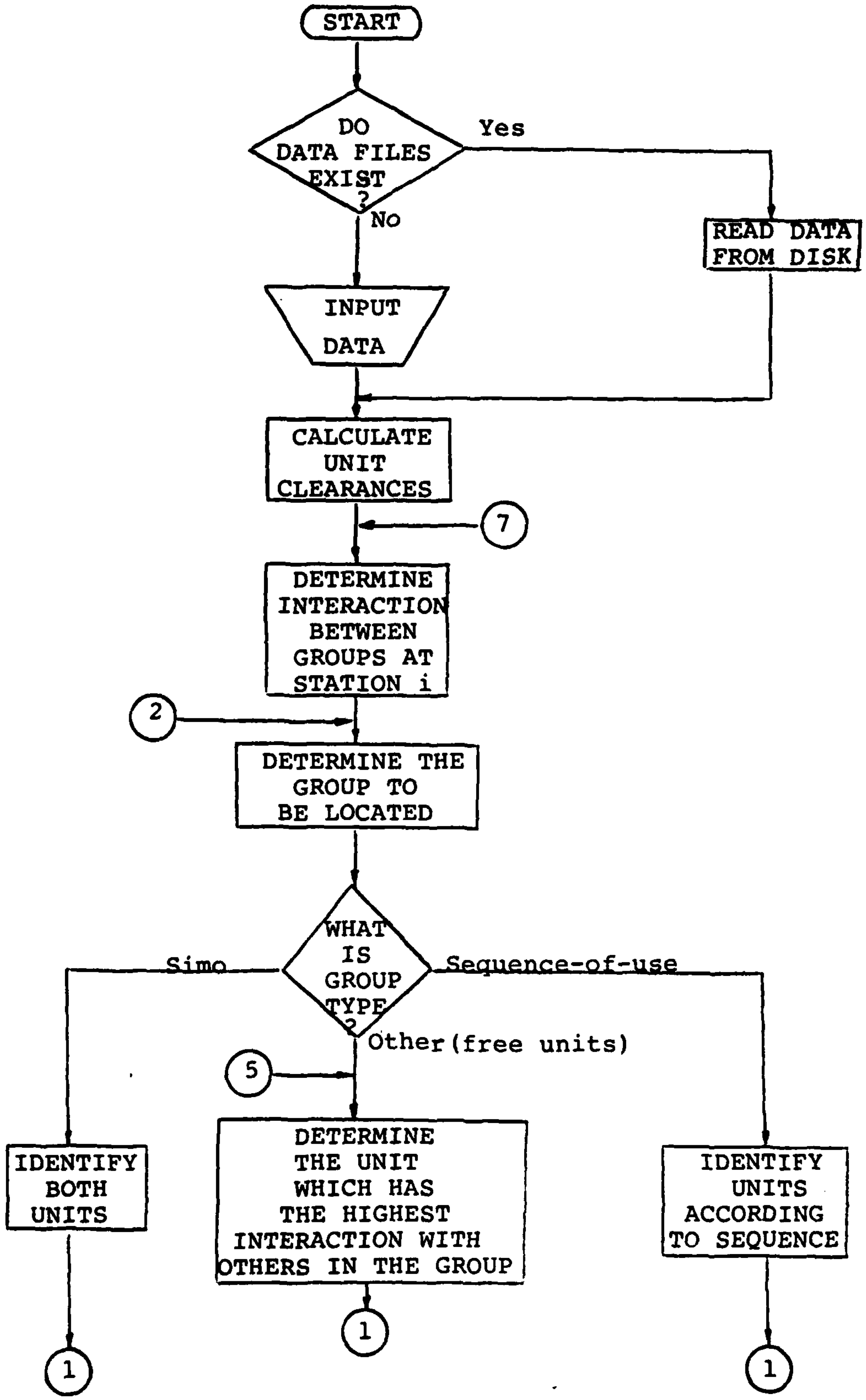


Figure 5. Flowchart of WOLAG

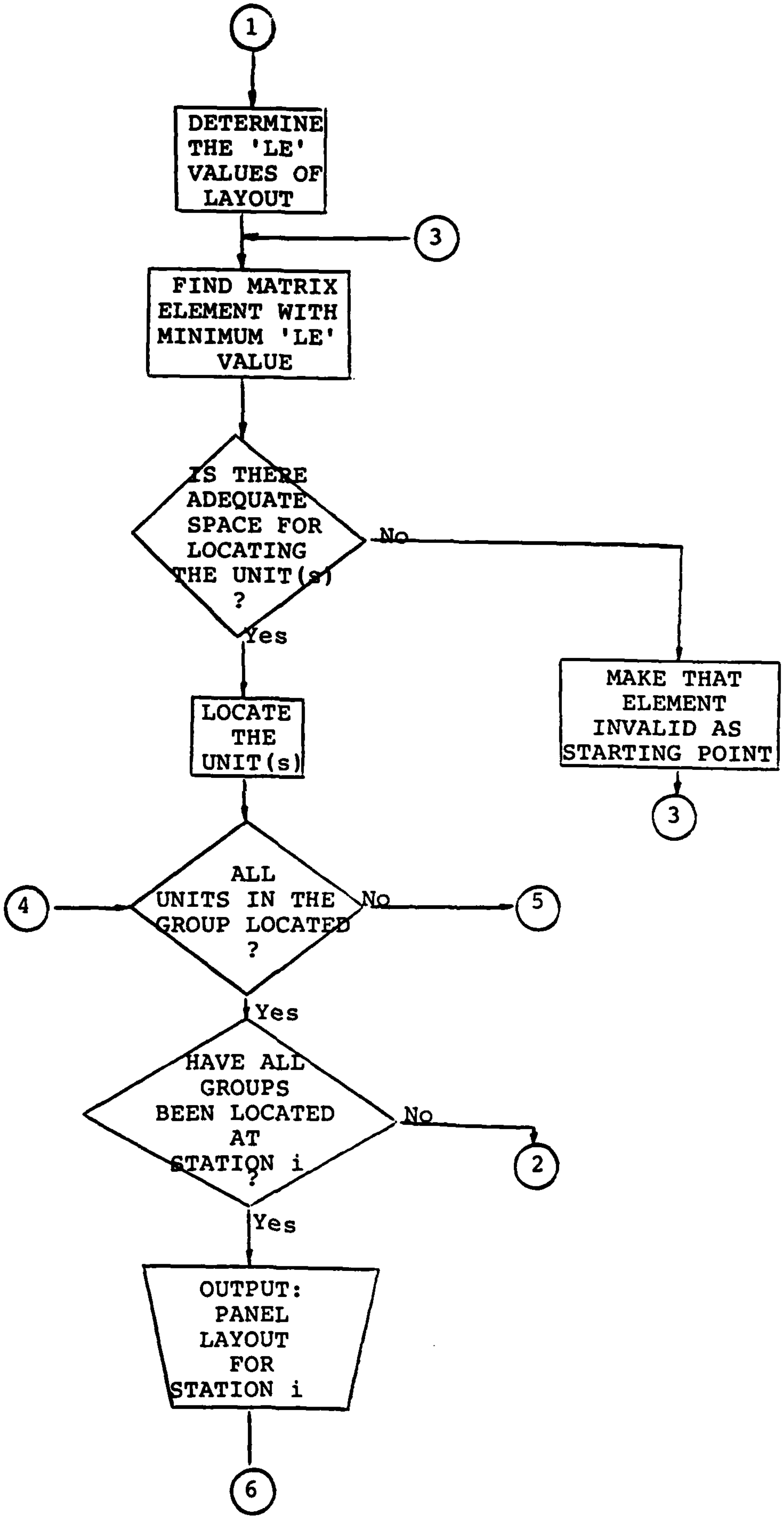


Figure 5. (continued)

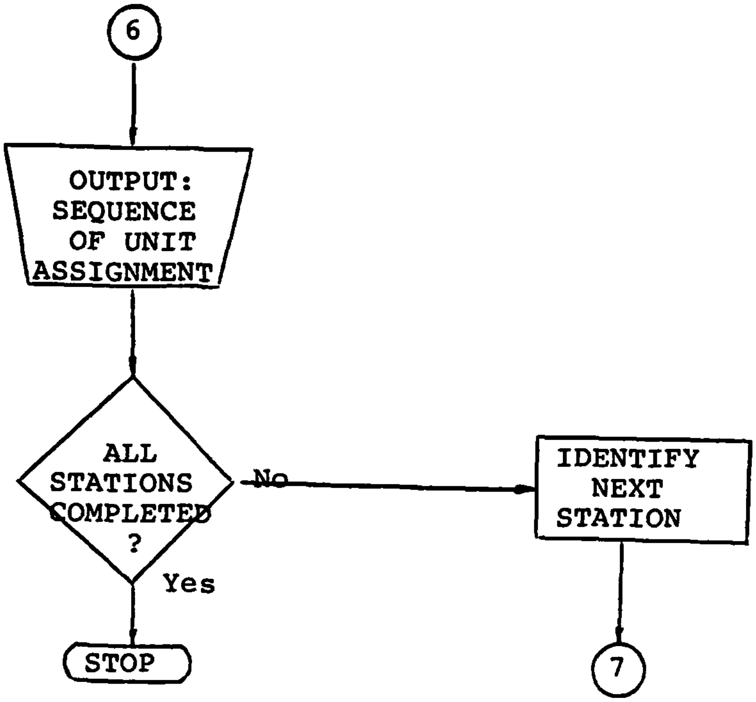


Figure 5. (continued)

Location of functional groups of displays and/or controls starts with the one possessing highest interaction with other groups. Once all the units belonging to that particular group have been located, the sequence-of-use data between groups is checked, and exhausted if any such data has been specified involving the group already located. Next, all the remaining functional groups are evaluated with respect to operational relationships between their members units and the units belonging to the groups already located. The group with the highest interrelationship (interaction) is located, and a second check of sequence-of-use data between functional groups is performed. This sequence continues until all functional groups of displays and controls have been located on the panel.

The interaction (operational relationship) between functional groups, if no sequence-of-use data has been specified, is calculated as follows:

$$INT_{ij} = \sum_{\ell} \sum_{m>\ell} (CR_{\ell i} + CR_{mj}) * IRAT_{\ell i,mj}$$

where:

INT_{ij} : Interaction (or link) value between ith and jth functional groups.

$CR_{\ell i}$: Criticality code of ℓth unit in the ith group.

CR_{mj} : Criticality code of mth unit in the jth group.

$IRAT_{\ell i,mj}$: Sequential link rating between the above units.

The locational effectiveness (LE) calculation is slightly different from the one in WORG:

$$LE_j = \sum_{i} ED_{ij} * IRAT_{ic} + P_c$$

where:

LE_j : Locational effectiveness of jth empty grid element

ED_{ij} : Euclidean distance between the centroid of the ith already located unit and the jth grid element.

$IRAT_{ic}$: Sequential link rating between the ith located unit and the candidate (c) unit.

P_c : Zonal Penalty associated with the criticality code of the candidate (c) unit and the locational priority zone within which jth empty grid element lies.

In order to ensure that the proposed layout fits to the human characteristics, several cautions have been exercised during planning the physical dimensions, shape, and partitions of the panels. Major ones are:

1. Workspace Geometry
2. Visual Space
3. Locational Priority Zones

The workspace geometry considerations arise from the need of constraining overall physical dimensions of the instrument panel so that all controls will be within reach distances, and the information presented by displays can be read accurately with minimal visual parallax. Constraints on the panel size have been imposed on all directions from the seat reference point. If two operators have been assigned to a workstation, physical dimensions on the horizontal axis double.

Anthropometric and visual characteristics of at least 90% of adult U.S. population have been considered in defining the physical panel dimensions. Critical anthropometric variables that controlled the design process are depth of reach, eye height, and shoulder height (Diffrient et al. 1983).

For a given panel, there are three sections on which displays and controls can be located through WOLAG: a) vertical top section b) an inclined upper-middle

section and c) an inclined lower-middle section. A horizontal front section is reserved as writing surface (see Figure 6). The lengths, and the angles between these sections have been generated through the visual space considerations on the vertical axis. Comfortable angular dimensions through eye and head movements in the vertical axis (Woodson, 1981), along with recommendations on preferred placement of different types of units around the Normal Line of Sight (McCormick and Sanders, 1982) were the major inputs to generating unit locational priority zones on the panel. These are partitions of the panel which establish relative utilities of various sections for locating different display and/or control types, such as warning displays, secondary controls, auxiliary displays, etc. The above considerations, along with Lazet's (1977) recommendations on panel partitioning resulted in the priority zones given by Figure 7.

Some other ergonomic design considerations exercised during locating displays and controls on the panel are:

1. Locating primary units in central locations, and placing secondary and auxiliary units following and around the critical ones.

2. Placing less frequently used units at peripheral locations with displays in the upper portions and controls in lower portions of the panel.

3. Locating functional groups from left to right of the panel to the extent allowed by other location considerations.

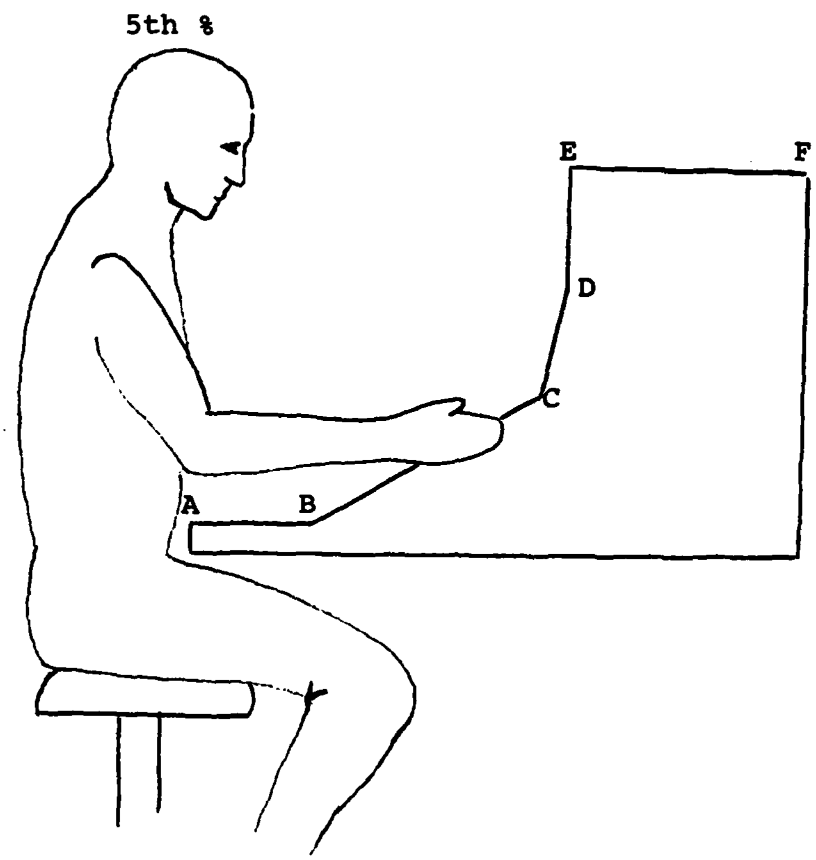
4. Locating simo-controls in the same general area.

5. Locating controls with adequate clearances in between in order to minimize accidental activation.

Outputs

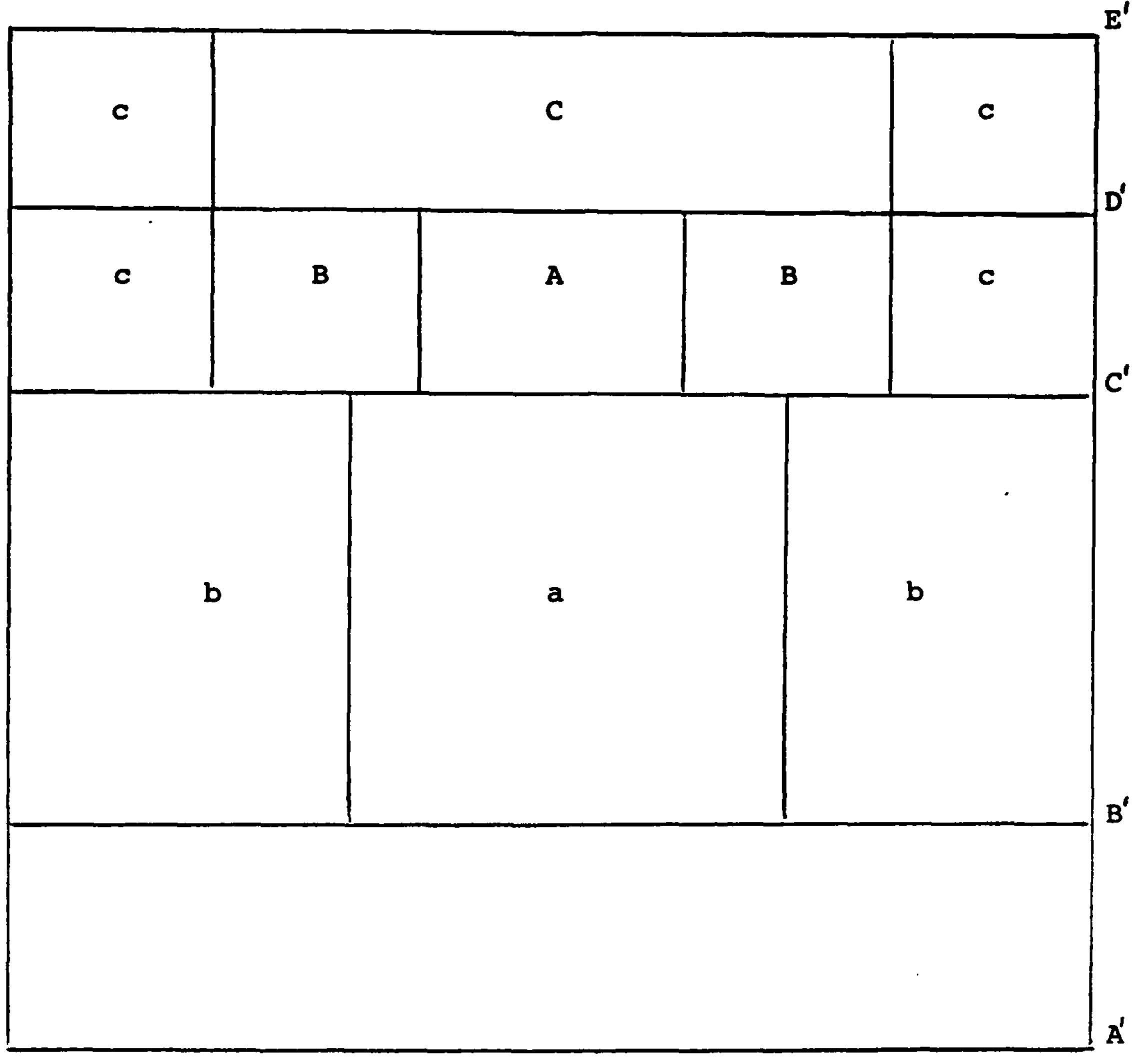
WOLAG outputs the following for each workstation:

a) A layout matrix of the instrument panel complete with unit assignments, and unused portions, if any.



AB=15.72cm ∡ B=150°
BC=32.18cm ∡ C=135°
CD=14.10cm ∡ D=165°
DE=14.38cm
EF=31.00cm

Figure 6. Geometric Relationships at the Workstation



	Primary Displays	Secondary Displays	Auxiliary Displays	Primary Controls	Secondary Controls	Auxiliary Controls
Area Code	A	B	C	a	b	c
Width Ratio	.2625	.2125	.6876	.4000	.3000	.1562

Figure 7. Unit Locational Priority Zones on the Panel

b) Placement sequence of the units on the panel.

c) Evaluative measures on the designs generated:

1. Total Links Value: Similar to the one in WORG.

2. Average Zone Deviation: Calculated as follows.

$$AZD = \sum_i ZD_i/M$$

where

AZD: Average Zone Deviation

ZD_i: Zone deviation value for ith unit. This is the euclidean distance between the centroid of the ith unit and the centroid of the closest appropriate zone.

M : Total number of units on the panel.

3. Total Zone Deviation: Numerator of the AZD equation.

If several panel designs are acceptable at any workstation, the one which minimizes the above statistics may be desirable.

Appendix III gives sample outputs of WOLAG for two workstations. Alternate panel layouts can be obtained at any station by specifying different input data for each run of the model. The layout which minimizes the evaluative measures may be considered for implementation.

SAINT-SYSTEM ANALYSIS OF INTEGRATED NETWORK OF TASKS

In MAWADES, dynamic evaluation of alternate design proposals is carried out using the SAINT model.

The original version of SAINT was developed by Pritsker et al. (1974). In network form, SAINT models sets of tasks performed during a mission of a man-machine system by one or several operators. At the end of the mission, performance measures can be obtained so that alternative system configurations having the same objective may be evaluated. Thus, SAINT allows the user to portray an actual mission of the operator-panel system in graphical form, and to convert this network of tasks into coded input in order to analyze time-dependent behavior of the system portrayed. Since SAINT is a computerized system, the impact of alternative configurations of the man-machine system on overall system performance can be investigated without major investment in equipment and manpower. Also, since there is no need of prototype hardware development, the result is an enormous savings of time and money.

SAINT has been reshaped by the same authors several times, each version adding new capabilities to this modeling procedure and analysis technique. The version used in the present study is the latest version finalized in 1978 (Wortman et al.). The user has to refer to the SAINT User's Manual to prepare and input data to the evaluation phase.

A SAINT network (mission) is represented through nodes and arrows; nodes corresponding to tasks (eye, hand, and body movements, display reading, control manipulation actions, control of simulation time, demand generation for operator actions through various indicator positions or system status information on displays), and arrows representing precedence relations between tasks. Thus,

for a typical mission of a crew, one can construct a network of tasks, and assigning probabilistic or deterministic performance times to the tasks, one can simulate the behavior of the system for extended periods of time (6,8 hrs. or more).

SAINT allows the user to collect various statistics during a simulation. MAWADES makes use of this attribute of SAINT to collect dynamic (time - dependent) evaluative measures on alternate panel configurations introducing human operators into the system and defining various missions to the system. Some of the dynamic evaluative measures which may be collected through SAINT are:

a) Eye, right hand, and left hand utilization rates. The particular system configuration which minimizes the above would be considered timewise less stressful, thus, "the better" design.

b) Average time elapsed between two successive occurances of a key event in the network. This measure gives average cycle time information. The particular crew station design configuration which allows the operators complete one set of repetitive actions in the least time would be considered to be the best.

c) Total time taken by the mission. The best design will be the one which allows the system complete the overall mission in the least amount of time.

d) Mean operator activity completion times after realization of abnormal conditions presented through various displays. The operator actions expected under several abnormal system conditions may be represented on the same network of tasks representing the mission. Furthermore, the reliability of the operator in carrying

out these actions may be indicated on the model. Then, at several occasions during the mission, demand may be generated for such actions through displaying various degrees of abnormal conditions on different displays. These conditions will trigger alternate operator actions to bring the system back to "normal". Naturally, the faster the operators are allowed to complete compensatory actions, the better the design is. Since the above statistic is collected over all displays which present disturbed system status information, a weighted analysis may be required to calculate a "merit index" for each layout.

e) Average time elapsed between the onset of a condition requiring operator action (presented through various displays), and the event which completes all operator actions to bring the system back to normal status. The dynamic evaluative measure previously presented marks the time when an operator realizes an abnormal condition, and collects interval statistics between the time operator completes all remedial actions and the marked time. However, time may pass between the onset of a condition requiring compensatory actions and actual realization of this condition by the operator. The measure currently being discussed collects interval statistics starting from the onset of an abnormal condition until the moment all remedial actions have been completed.

CONCLUSIONS

MAWADES is a computerized tool for crew station design. Members of the crew are assumed to be engaged in command, communications, and control activities using instrument panels at sit-stand duty.

A unique characteristic of MAWADES is that each module can be used separately or in different combinations with the other modules. One can use WOSTAS to assign mission tasks to workstations for workload balancing. Work-space design decisions can be made through WORG in a matter of minutes. Panel layouts at each workstation can be obtained in a matter of hours. SAINT model can be utilized independently, to evaluate alternate crew station designs obtained through other means if not through other modules of MAWADES. When all modules are used in succession, a major design problem can be solved in a day or two.

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APPENDIX I. WOSTAS output for the example problem

```
 CYCLE TIME= 16.0MINUTES
TASKS ASSIGNED TO EACH WORKSTATION
WORKSTATION  1:   BALANCE DELAY= 0.0MINUTES
TASK NUMBER         EXPECTED DURATION
       1                    5.0000
       2                    3.0000
       4                    4.0000
       9                    4.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  1
TIRING MEAN= 1.3
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .40         .41          .67          .56
std.dev.  0.2055      0.2445       0.3332       0.2025
WORKSTATION  2:   BALANCE DELAY= 3.1MINUTES
TASK NUMBER         EXPECTED DURATION
      14                    7.0000
       3                    2.0000
       8                    0.6000
      20                    3.3000
ABILITY AND TIRING CHARACTERISTICS AT W/S  2
TIRING MEAN= 1.3
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .59         .41          .54          .40
std.dev.  0.2698      0.3033       0.2859       0.1590
WORKSTATION  3:   BALANCE DELAY= 5.5MINUTES
TASK NUMBER         EXPECTED DURATION
      19                   10.5000
ABILITY AND TIRING CHARACTERISTICS AT W/S  3
TIRING MEAN= 2.0
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .40         .53          .80          .80
std.dev.  0.0000      0.0000       0.0000       0.0000
WORKSTATION  4:   BALANCE DELAY= 1.2MINUTES
TASK NUMBER         EXPECTED DURATION
      26                    5.6000
      12                    1.4400
       5                    4.8000
      13                    0.1800
      33                    2.1000
      18                    0.1200
      17                    0.5400
ABILITY AND TIRING CHARACTERISTICS AT W/S  4
```

```
MEAN      .18         .24          .35           .
std.dev.  0.2677      0.3719       0.2271        0.0749
WORKSTATION  5:   BALANCE DELAY= 0.0MINUTES
TASK NUMBER          EXPECTED DURATION
      6                      6.4000
      7                      4.0000
     11                      1.6000
     16                      2.4000
     24                      1.6000
ABILITY AND TIRING CHARACTERISTICS AT W/S  5
TIRING MEAN= 1.2
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN         .46         .43          .55           .59
std.dev.  0.5859      0.2144       0.2564        0.3122
WORKSTATION  6:   BALANCE DELAY= 0.5MINUTES
TASK NUMBER          EXPECTED DURATION
     25                      3.0000
     30                      2.0800
     23                      1.2800
     22                      2.4000
     29                      6.7584
ABILITY AND TIRING CHARACTERISTICS AT W/S  6
TIRING MEAN= 1.6
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN         .27         .38          .48           .70
std.dev.  0.0941      0.2286       0.1810        0.1895
WORKSTATION  7:   BALANCE DELAY= 3.0MINUTES
TASK NUMBER          EXPECTED DURATION
     31                      8.4480
     36                      3.2000
     32                      1.4000
ABILITY AND TIRING CHARACTERISTICS AT W/S  7
TIRING MEAN= 1.3
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN         .61         .54          .33           .44
std.dev.  0.1829      0.0093       0.1861        0.3101
WORKSTATION  8:   BALANCE DELAY= 5.0MINUTES
TASK NUMBER          EXPECTED DURATION
     10                      3.0000
     15                      8.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  8
TIRING MEAN= 1.0
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN         .53         .50          .50           .61
std.dev.  0.2553      0.1233       0.4604        0.6067
WORKSTATION  9:   BALANCE DELAY= 0.0MINUTES
TASK NUMBER          EXPECTED DURATION
     21                     10.0000
```

```
std.dev.  0.3061        0.1117        0.2250        0.1607
WORKSTATION 10:   BALANCE DELAY= 1.0MINUTES
TASK NUMBER         EXPECTED DURATION
     28                     9.0000
     34                     4.0000
     35                     2.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S 10
TIRING MEAN= 2.0
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN       .48          .48          .45          .51
std.dev.  0.0457        0.0182        0.2626        0.4208
WORKSTATION 11:   BALANCE DELAY= 4.0MINUTES
TASK NUMBER         EXPECTED DURATION
     37                    12.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S 11
TIRING MEAN= 1.0
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN       .62          .21          .24          .48
std.dev.  0.0000        0.0000        0.0000        0.0000
WORKSTATION 12:   BALANCE DELAY= 3.0MINUTES
TASK NUMBER         EXPECTED DURATION
     38                     6.0000
     39                     7.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S 12
TIRING MEAN= 2.0
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN       .51          .59          .53          .59
std.dev.  0.1331        0.1622        0.3730        0.4118
TOTAL BALANCE DELAY=   26.2536



 CYCLE TIME= 19.0MINUTES
TASKS ASSIGNED TO EACH WORKSTATION
WORKSTATION  1:   BALANCE DELAY= 0.4MINUTES
TASK NUMBER         EXPECTED DURATION
      1                     5.0000
      2                     3.0000
      4                     4.0000
      9                     4.0000
      3                     2.0000
      8                     0.6000
```

```
MEAN                                          .54
std.dev.  0.2555      0.2365      0.3041      0.1802
WORKSTATION  2:   BALANCE DELAY= 1.5MINUTES
TASK NUMBER         EXPECTED DURATION
     14                   7.0000
     19                  10.5000
ABILITY AND TIRING CHARACTERISTICS AT W/S  2
TIRING MEAN= 1.5
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN       .31         .38         .53         .55
std.dev.  0.1291      0.2234      0.3812      0.3505
WORKSTATION  3:   BALANCE DELAY= 0.9MINUTES
TASK NUMBER         EXPECTED DURATION
     26                   5.6000
     12                   1.4400
      5                   4.8000
     13                   0.1800
     33                   2.1000
     18                   0.1200
     20                   3.3000
     17                   0.5400
ABILITY AND TIRING CHARACTERISTICS AT W/S  3
TIRING MEAN= 1.4
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN       .67         .57         .40         .22
std.dev.  0.2505      0.3541      0.2588      0.0744
WORKSTATION  4:   BALANCE DELAY= 0.9MINUTES
TASK NUMBER         EXPECTED DURATION
      6                   6.4000
      7                   4.0000
     11                   1.6000
     16                   2.4000
     22                   2.4000
     23                   1.2800
ABILITY AND TIRING CHARACTERISTICS AT W/S  4
TIRING MEAN= 1.5
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN       .44         .44         .48         .59
std.dev.  0.5191      0.1862      0.2061      0.2731
WORKSTATION  5:   BALANCE DELAY= 4.2MINUTES
TASK NUMBER         EXPECTED DURATION
     29                   6.7584
     24                   1.6000
     25                   3.0000
     30                   2.0800
     32                   1.4000
ABILITY AND TIRING CHARACTERISTICS AT W/S  5
TIRING MEAN= 1.4
```

```
WORKSTATION     BALANCE DELAY= 7.4MINUTES
TASK NUMBER         EXPECTED DURATION
     31                     8.4480
     36                     3.2000
ABILITY AND TIRING CHARACTERISTICS AT W/S  6
TIRING MEAN= 1.0
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .68          .55          .38          .26
std.dev.  0.1928       0.0000       0.2357       0.0214
WORKSTATION  7:   BALANCE DELAY= 8.0MINUTES
TASK NUMBER         EXPECTED DURATION
     10                     3.0000
     15                     8.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  7
TIRING MEAN= 1.0
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .53          .50          .50          .61
std.dev.  0.2553       0.1233       0.4604       0.6067
WORKSTATION  8:   BALANCE DELAY= 0.0MINUTES
TASK NUMBER         EXPECTED DURATION
     21                    10.0000
     28                     9.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  8
TIRING MEAN= 1.0
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .43          .49          .78          .28
std.dev.  0.0143       0.0107       0.0482       0.0036
WORKSTATION  9:   BALANCE DELAY= 7.0MINUTES
TASK NUMBER         EXPECTED DURATION
     27                     6.0000
     34                     4.0000
     35                     2.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  9
TIRING MEAN= 2.0
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .62          .53          .37          .59
std.dev.  0.2075       0.1006       0.1210       0.3755
WORKSTATION 10:   BALANCE DELAY= 1.0MINUTES
TASK NUMBER         EXPECTED DURATION
     37                    12.0000
     38                     6.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S 10
TIRING MEAN= 1.0
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .61          .45          .25          .39
std.dev.  0.0146       0.3487       0.0179       0.1292
WORKSTATION 11:   BALANCE DELAY=12.0MINUTES
TASK NUMBER         EXPECTED DURATION
```

```
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .41          .47          .79          .88
std.dev.  0.0000       0.0000       0.0000       0.0000
TOTAL BALANCE DELAY=   43.2536



 CYCLE TIME= 22.0MINUTES
TASKS ASSIGNED TO EACH WORKSTATION
WORKSTATION  1:   BALANCE DELAY= 3.4MINUTES
TASK NUMBER         EXPECTED DURATION
      1                     5.0000
      2                     3.0000
      4                     4.0000
      9                     4.0000
      3                     2.0000
      8                     0.6000
ABILITY AND TIRING CHARACTERISTICS AT W/S  1
TIRING MEAN= 1.3
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .53          .38          .63          .54
std.dev.  0.2555       0.2365       0.3041       0.1802
WORKSTATION  2:   BALANCE DELAY= 1.2MINUTES
TASK NUMBER         EXPECTED DURATION
     14                     7.0000
     19                    10.5000
     20                     3.3000
ABILITY AND TIRING CHARACTERISTICS AT W/S  2
TIRING MEAN= 1.3
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .40          .51          .61          .46
std.dev.  0.1816       0.2792       0.3041       0.2903
WORKSTATION  3:   BALANCE DELAY= 3.2MINUTES
TASK NUMBER         EXPECTED DURATION
     26                     5.6000
     12                     1.4400
      5                     4.8000
     13                     0.1800
     33                     2.1000
     18                     0.1200
     17                     0.5400
      7                     4.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  3
```

```
std.dev. [illegible]   [illegible]   [illegible]   0.1580
WORKSTATION  4:   BALANCE DELAY= 0.6MINUTES
TASK NUMBER         EXPECTED DURATION
      6                  6.4000
     11                  1.6000
     16                  2.4000
     10                  3.0000
     15                  8.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  4
TIRING MEAN= 1.2
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .61         .49          .49          .53
std.dev.  0.5357      0.1905       0.3199       0.4029
WORKSTATION  5:   BALANCE DELAY= 0.1MINUTES
TASK NUMBER         EXPECTED DURATION
     21                 10.0000
     28                  9.0000
     24                  1.6000
     23                  1.2800
ABILITY AND TIRING CHARACTERISTICS AT W/S  5
TIRING MEAN= 1.3
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .30         .42          .72          .57
std.dev.  0.1603      0.1304       0.1367       0.3454
WORKSTATION  6:   BALANCE DELAY= 0.8MINUTES
TASK NUMBER         EXPECTED DURATION
     27                  6.0000
     34                  4.0000
     35                  2.0000
     22                  2.4000
     29                  6.7584
ABILITY AND TIRING CHARACTERISTICS AT W/S  6
TIRING MEAN= 1.8
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .46         .41          .35          .66
std.dev.  0.2621      0.1808       0.0970       0.3055
WORKSTATION  7:   BALANCE DELAY= 1.6MINUTES
TASK NUMBER         EXPECTED DURATION
     37                 12.0000
     31                  8.4480
ABILITY AND TIRING CHARACTERISTICS AT W/S  7
TIRING MEAN= 1.0
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .58         .38          .23          .36
std.dev.  0.0532      0.2394       0.0207       0.1699
WORKSTATION  8:   BALANCE DELAY= 6.3MINUTES
TASK NUMBER         EXPECTED DURATION
     25                  3.0000
```

```
                   0.3330        0.2659        0.2215
WORKSTATION  3:   BALANCE DELAY= 0.2MINUTES
TASK NUMBER         EXPECTED DURATION
      6                     6.4000
      7                     4.0000
     11                     1.6000
     10                     3.0000
     15                     8.0000
     16                     2.4000
     22                     2.4000
ABILITY AND TIRING CHARACTERISTICS AT W/S  3
TIRING MEAN= 1.3
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .50         .45          .48          .55
std.dev.  0.4762      0.1800       0.2659       0.3320
WORKSTATION  4:   BALANCE DELAY= 1.0MINUTES
TASK NUMBER         EXPECTED DURATION
     21                    10.0000
     28                     9.0000
     24                     1.6000
     25                     3.0000
     30                     2.0800
     23                     1.2800
ABILITY AND TIRING CHARACTERISTICS AT W/S  4
TIRING MEAN= 1.3
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .32         .44          .69          .56
std.dev.  0.1393      0.1926       0.1401       0.2692
WORKSTATION  5:   BALANCE DELAY= 0.2MINUTES
TASK NUMBER         EXPECTED DURATION
     29                     6.7584
     35                     2.0000
     32                     1.4000
     31                     8.4480
     27                     6.0000
     36                     3.2000
ABILITY AND TIRING CHARACTERISTICS AT W/S  5
TIRING MEAN= 1.5
          LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .57         .49          .35          .62
std.dev.  0.2420      0.1521       0.1415       0.3318
WORKSTATION  6:   BALANCE DELAY= 6.0MINUTES
TASK NUMBER         EXPECTED DURATION
     34                     4.0000
     37                    12.0000
     38                     6.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  6
TIRING MEAN= 1.3
```

```
TASK NUMBER          EXPECTED DURATION
   39                       7.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  7
TIRING MEAN= 3.0
           LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN          .41         .47          .79         .88
std.dev.  0.0000       0.0000       0.0000      0.0000
TOTAL BALANCE DELAY=   30.2536



 CYCLE TIME= 31.0MINUTES
TASKS ASSIGNED TO EACH WORKSTATION
WORKSTATION  1:   BALANCE DELAY= 2.1MINUTES
TASK NUMBER          EXPECTED DURATION
    1                       5.0000
    2                       3.0000
    4                       4.0000
    9                       4.0000
   14                       7.0000
   20                       3.3000
    3                       2.0000
    8                       0.6000
ABILITY AND TIRING CHARACTERISTICS AT W/S  1
TIRING MEAN= 1.3
           LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN          .50         .41          .60         .48
std.dev.  0.2446       0.2551       0.2958      0.1891
WORKSTATION  2:   BALANCE DELAY= 1.7MINUTES
TASK NUMBER          EXPECTED DURATION
   19                      10.5000
    5                       4.8000
   12                       1.4400
   13                       0.1800
   26                       5.6000
   33                       2.1000
   18                       0.1200
   17                       0.5400
    7                       4.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  2
TIRING MEAN= 1.4
           LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
```

TASK NUMBER	EXPECTED DURATION
6	6.4000
11	1.6000
16	2.4000
10	3.0000
15	8.0000
22	2.4000
23	1.2800
24	1.6000

ABILITY AND TIRING CHARACTERISTICS AT W/S 3
TIRING MEAN= 1.4

	LANGUAGE	INTELLECTUAL	PERCEPTUAL	PSYCHOMOTOR
MEAN	.45	.42	.51	.63
std.dev.	0.4586	0.1855	0.2676	0.3422

WORKSTATION 4: BALANCE DELAY= 0.2MINUTES

TASK NUMBER	EXPECTED DURATION
21	10.0000
28	9.0000
30	2.0800
25	3.0000
29	6.7584

ABILITY AND TIRING CHARACTERISTICS AT W/S 4
TIRING MEAN= 1.2

	LANGUAGE	INTELLECTUAL	PERCEPTUAL	PSYCHOMOTOR
MEAN	.35	.44	.62	.51
std.dev.	0.1168	0.2210	0.2304	0.2703

WORKSTATION 5: BALANCE DELAY= 6.0MINUTES

TASK NUMBER	EXPECTED DURATION
31	8.4480
27	6.0000
34	4.0000
36	3.2000
32	1.4000
35	2.0000

ABILITY AND TIRING CHARACTERISTICS AT W/S 5
TIRING MEAN= 1.7

	LANGUAGE	INTELLECTUAL	PERCEPTUAL	PSYCHOMOTOR
MEAN	.62	.53	.35	.51
std.dev.	0.1750	0.0643	0.1417	0.3190

WORKSTATION 6: BALANCE DELAY= 6.0MINUTES

TASK NUMBER	EXPECTED DURATION
37	12.0000
38	6.0000
39	7.0000

ABILITY AND TIRING CHARACTERISTICS AT W/S 6
TIRING MEAN= 1.7

	LANGUAGE	INTELLECTUAL	PERCEPTUAL	PSYCHOMOTOR
MEAN	.54	.46	.43	.56

```
 CYCLE TIME= 34.0MINUTES
TASKS ASSIGNED TO EACH WORKSTATION
WORKSTATION  1:   BALANCE DELAY= 0.5MINUTES
TASK NUMBER          EXPECTED DURATION
       1                      5.0000
       2                      3.0000
       4                      4.0000
       9                      4.0000
      14                      7.0000
      19                     10.5000
ABILITY AND TIRING CHARACTERISTICS AT W/S  1
TIRING MEAN= 1.3
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .37         .40          .62          .56
std.dev.  0.1762       0.2148       0.3172       0.2218
WORKSTATION  2:   BALANCE DELAY= 2.3MINUTES
TASK NUMBER          EXPECTED DURATION
      26                      5.6000
      33                      2.1000
      10                      3.0000
      15                      8.0000
       3                      2.0000
       8                      0.6000
      13                      0.1800
       5                      4.8000
      12                      1.4400
      18                      0.1200
      20                      3.3000
      17                      0.5400
ABILITY AND TIRING CHARACTERISTICS AT W/S  2
TIRING MEAN= 1.3
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .67         .52          .44          .33
std.dev.  0.2286       0.3141       0.2761       0.2597
WORKSTATION  3:   BALANCE DELAY= 1.0MINUTES
TASK NUMBER          EXPECTED DURATION
      21                     10.0000
      28                      9.0000
       6                      6.4000
       7                      4.0000
      11                      1.6000
```

```
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .35          .44          .62          .59
std.dev.  0.1398       0.0971       0.1971       0.2863
WORKSTATION  4:   BALANCE DELAY= 4.3MINUTES
TASK NUMBER          EXPECTED DURATION
      27                    6.0000
      16                    2.4000
      34                    4.0000
      37                   12.0000
      22                    2.4000
      23                    1.2800
      24                    1.6000
ABILITY AND TIRING CHARACTERISTICS AT W/S  4
TIRING MEAN= 1.4
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .58          .43          .41          .53
std.dev.  0.4811       0.2143       0.2098       0.2938
WORKSTATION  5:   BALANCE DELAY= 3.1MINUTES
TASK NUMBER          EXPECTED DURATION
      29                    6.7584
      25                    3.0000
      30                    2.0800
      32                    1.4000
      31                    8.4480
      36                    3.2000
      38                    6.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  5
TIRING MEAN= 1.3
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .47          .50          .40          .52
std.dev.  0.2106       0.2081       0.2048       0.2691
WORKSTATION  6:   BALANCE DELAY=27.0MINUTES
TASK NUMBER          EXPECTED DURATION
      39                    7.0000
ABILITY AND TIRING CHARACTERISTICS AT W/S  6
TIRING MEAN= 3.0
         LANGUAGE INTELLECTUAL PERCEPTUAL PSYCHOMOTOR
MEAN        .41          .47          .79          .88
std.dev.  0.0000       0.0000       0.0000       0.0000
TOTAL BALANCE DELAY=   38.2536
STOP

END OF EXECUTION
CPU TIME: 26.55 ELAPSED TIME: 5:1.98
EXIT

.kJob
Job 28  User MAWADES [3030,30]
```

APPENDIX II. A Sample WORG Output

```
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0181818 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0111111111111313131313 9 9 9 9 9 8 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0111111111111313131313 9 9 9 9 9 8 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0111111111111313131313 9 9 9 9 [illegible] 8 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0111111111111313131313 9 9 9 9 [illegible] [illegible] 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

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0 0 0 0 0 0 011111111111131313131313 9 9 9 9 9 8 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 011111111111131313131313 9 9 9 9 9 8 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 011111111111131313131313 9 9 9 9 9 8 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 011111111111131313131313 9 9 9 9 9 8 8 8 8 81010101010 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 01414141414121212121212 5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 01414141414121212121212 5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 3 3 3 3 31717171717151515151515 4 4 4 4 41616161616 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 3 3 3 3 31717171717151515151515 4 4 4 4 41616161616 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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```

TOTAL LINK FOR THIS LAYOUT IS 4239

SEQUENCE OF ASSIGNMENT

18 **

6

5

7

8

9

10

12

13

15

17

4

3

1

2

14

16

11

** DENOTES COMMON PANELS

APPENDIX III. A Sample WOLAG Output

LAYOUT FOR PANEL 1

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
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13	13	13	13	13	13	13	13	13	13	13	13	0	27	27	27	27	27	27	27	27	27	27	27	28	28	28	
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13	13	13	13	13	13	13	13	13	13	13	13	0	27	27	27	27	27	27	27	27	27	27	27	28	28	28	
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13	13	13	13	13	13	13	13	13	13	13	13	0	27	27	27	27	27	27	27	27	27	27	27	28	28	28	
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13	13	13	13	13	13	13	13	13	13	13	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13	13	13	13	13	13	13	13	13	13	13	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
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2	12	12	12	0	24	24	24	24	24	24	24	24	24	24	24	24	24	24	0	15	15	15	15	15	0	6	6	6	6	6	6	6	6	6
2	12	12	12	0	24	24	24	24	24	24	24	24	24	24	24	24	24	24	0	15	15	15	15	15	0	6	6	6	6	6	6	6	6	6
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0	10	10	10	10	10	10	10	10	10	10	10	10	10	0	25	25	25	25	25	25	26	26	26	26	0	6	6	6	6	6	6	6	6	6
0	10	10	10	10	10	10	10	10	10	10	10	10	10	0	25	25	25	25	25	25	0	0	0	0	0	6	6	6	6	6	6	6	6	6
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0	10	10	10	10	10	10	10	10	10	10	10	10	10	0	0	0	14	14	14	14	14	14	14	14	14	14	14	14	14	14	17	17	17	17
1	21	21	21	0	18	18	18	18	18	18	18	18	18	18	18	0	14	14	14	14	14	14	14	14	14	14	14	14	14	14	17	17	17	17
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1	21	21	21	0	18	18	18	18	18	18	18	18	18	18	18	0	0	23	23	23	23	23	23	0	0	0	0	0	0	0	0	0	0	0
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SEQUENCE OF UNIT LOCATION

29
1
15
26
6
3
4
7
28
27
16
5
17
14
2
8
24
25
9
10

11
12
13
18
19
20
21
22
23

TOTAL LINKS FOR THIS LAYOUT = 602.84

UNIT # 2 WAS LOCATED OUT OF ZONE
UNIT # 8 WAS LOCATED OUT OF ZONE
UNIT # 24 WAS LOCATED OUT OF ZONE
UNIT # 25 WAS LOCATED OUT OF ZONE
UNIT # 9 WAS LOCATED OUT OF ZONE
UNIT # 10 WAS LOCATED OUT OF ZONE
UNIT # 11 WAS LOCATED OUT OF ZONE
UNIT # 12 WAS LOCATED OUT OF ZONE
UNIT # 13 WAS LOCATED OUT OF ZONE
UNIT # 18 WAS LOCATED OUT OF ZONE
UNIT # 19 WAS LOCATED OUT OF ZONE
UNIT # 20 WAS LOCATED OUT OF ZONE
UNIT # 21 WAS LOCATED OUT OF ZONE
UNIT # 22 WAS LOCATED OUT OF ZONE
UNIT # 23 WAS LOCATED OUT OF ZONE

TOTAL ZONAL DEVIATION = 796.

ZONE DEVIATION PER UNIT = 27.45

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	9	0	0
0	13	0	0	27	0	0	28	0	0	0	0	7	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	24	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0

ZONE DEVIATION PER UNIT = 27.45

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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	13	0	0	27	0	0	28	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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